NACA

RESEARCH MEMORANDUM

TURBOJET COMBUSTOR EFFICIENCY AT HIGH ALTITUDES

By Walter T. Olson, J. Howard Childs, and
Edmund R. Jonash

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

NACA research on the single problem of combustion efficiency of turbojet engines at high altitudes is discussed. Representative results of investigations with turbojet combustors are presented to illustrate the trends obtained with the following categories of variables: (1) combustor operating variables, (2) combustor-design variables, and (3) fuel variables.

The data indicated that as the environment of the combustor becomes one of low pressure and low temperature at high altitude, low combustion efficiencies and limited values of obtainable temperature rise were encountered. Increased cross-sectional area of combustor for a given weight flow of air decreased velocities and facilitated high combustion efficiency at altitude. For the design of the liner, increased volume in the flame zone and gradual admission of the air into the combustion space were shown to aid combustion by helping to provide localized fuel-air mixtures of correct composition that exist sufficiently long for ignition and combustion to occur. For high combustion efficiency to occur, all the fuel must be involved in this manner, and it was shown that the combustor design, the fuel injection, and the fuel volatility must be matched if optimum combustion efficiency is to be achieved; in general, combustion efficiency decreased with increased fuel boiling temperatures. Further, it was shown that fuels of higher flame speed and/or lower ignition temperatures gave higher combustion efficiency when other properties were similar.

INTRODUCTION

The value of an aircraft propulsion system is measured in terms of the reliable delivery of required thrust for a minimum fuel-consumption rate, engine weight, engine frontal area, and engine cost for a range of speeds and operating altitudes. For turbojet engines, these factors impose many requirements on the combustion chamber; the principal factors are stability and reliability of operation, high combustion efficiency, small volume or size, minimum pressure drop, minimum weight, a preferred pattern of outlet-temperature distribution, strength and durability, ease of ignition, ability to utilize a variety of fuels, and ease of manufacture. Many of these requirements are in conflict with one another, such as high combustion efficiency as opposed to minimum combustor size. Although NACA research on turbojet combustors has necessarily concerned most of these requirements, the present report is restricted intentionally to only that part of research on turbojet combustion that has been concerned with combustion efficiency at high altitudes.

It is commonly understood that the effective operating regime of the turbojet engine is high flight speed and high altitude. Further, the service requirements of turbojet engines plainly call for effective operation at even higher and higher altitudes. Experience has shown that, as operating altitudes are progressively increased beyond 25,000 feet, the effects of altitude on combustion efficiency ultimately result in severe penalties in thrust and specific fuel consumption. The problem of maintaining high combustion efficiency is one of the most important problems of altitude operation.

The research approach to the problem has involved both systematic investigations of the effect of individual variables on combustor performance and attempts to relate fundamental combustion parameters, such as fuel-spray characteristics, ignition limits, and flame speeds to the observed combustor performance. Consequently, this report describes and discusses the individual effects of different variables on turbojet combustion efficiency. These variables are, for convenience, listed as operational variables (fuel-air ratio, and combustor inlet-air pressure, temperature, and velocity), design variables, and fuel variables. Although the shortcomings of trying to isolate variables or to apply fundamental data to a total process as complicated as the combustion process in a high-heat-release burner are recognized, an appreciation and an understanding of the combustion problem at altitude have been gained in this way.

The data presented are selected from a broad range of studies with many different combustors and are believed to be illustrative of the trends obtained. The data were obtained by operating individual combustors in installations supplied with air and exhaust services that permitted control of combustor inlet-air pressures, temperatures, and flow rates. Typical methods are described in references 1 and 2. Certain trends thus obtained have been verified with full-scale engine operation in research facilities that simulate altitude conditions.

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TURBOJET COMBUSTOR

The technique that is used to obtained the required combustion in turbine engines is dictated largely by the necessity of establishing a low-velocity zone having a fuel-air ratio near the stoichiometric value. The need for such a zone is evident from figures 1 and 2. Figure 1 (reference 3) shows the inflammability limits of quiescent gasoline-air mixtures obtained in simple bench-scale laboratory apparatus. For a given pressure, ignition is possible over only a limited range of fuel-air ratios near stoichiometric, and this range decreases with a decrease in pressure. Below a pressure of 0.7 pound per square inch, ignition is impossible at any fuel-air ratio. If combustion is to occur at all in a turbine engine, the pressure and the fuel-air ratio in the burning zone must lie within the envelope shown in figure 1.

Velocity can also make it impossible to obtain combustion if its values exceed certain limits. In figure 2 velocity is plotted as a function of fuel-air ratio. The lowest curve (from reference 4) in the figure shows flame velocities typical of mixtures of hydrocarbon fuels and air; if the flow velocity in the fuel-air mixture everywhere exceeds about 2 feet per second, the flame will be extinguished. The upper curve (from reference 5) delineates the limits for combustion of mixtures of vaporized gasoline and air burning downstream of a perforated plate arranged normal to the flow in a 2-inch-diameter tube. This perforated plate constitutes a flame shield very similar to that provided in turbojet combustors. Combustion could be maintained at fuel-air ratios and velocities corresponding to points lying beneath the upper curve; only at these conditions did the perforated plate provide adequate shielded zones where the velocity and the fuel-air ratio corresponded to values below the normal flame speeds shown by the lower curve. If combustion is to occur in a combustor, the velocities and the fuel-air ratios in the burning zone should correspond to points lying beneath the upper curve in figure 2. The shaded area in the figure indicates the range of over-all fuel-air ratios and velocities typical of current turbojet combustors. These values of fuel-air ratio and velocity were computed by methods described in a subsequent section of this paper and are approximate average values of these parameters within the combustors. It is evident from figure 2 that the combustor geometry should produce within the combustion zone fuel-air ratios that are much higher and velocities that are preferably much lower than the approximate average values lying within the shaded area in figure 2.

In current turbojet engines the combustors are of two general types, annular and tubular, as illustrated in figure 3. In both types of combustor, the air is admitted into the burning zone through perforations in a combustor liner; the passage of the air through these perforations is indicated by the arrows in figure 3. The fuel is injected as a liquid spray at the upstream end by means of pressure-atomizing nozzles. Most of the air is bypassed around the upstream end of the combustor and admitted farther downstream; only a fraction of the total air flow is therefore admitted directly through the perforations into the burning zone. This technique produces the low velocities shown to be necessary by the data of figure 2. Also, the injection of all the fuel but only a fraction of the air into the burning zone produces the high fuel-air ratios shown to be necessary by the data of figures 1 and 2.

The first essential in combustor design, then, is to provide conditions within the burning zone, which lie within the combustible range of velocities and fuel-air ratios. This provision becomes increasingly difficult as the pressure is lowered as shown by figure 1, and even with quiescent mixtures absolute pressure limits of inflammability exist.

In the turbojet combustor the problem, as previously stated, is one of maintaining a high combustion efficiency and, in addition, a high rate of heat release. Because of this requirement of a high heat-release rate, high velocities must be employed in the combustor; thermodynamic equilibrium is not achieved within the combustor; and combustion efficiencies below 100 percent are frequently obtained at adverse operating conditions. Figure 4 shows a plot of the combustion efficiencies obtained with a typical turbojet combustor over a range of simulated flight altitudes and engine rotor speeds. The efficiency progressively decreases with an increase in altitude and with a decrease in engine speed. Above the dashed curve, the engine is inoperable because the combustor cannot supply heat at the required rate to operate the turbine. The general phenomena and trends exhibited in figure 4 are encountered in all aircraft turbine engines. Figure 5 shows a plot of combustion efficiency against altitude for three different turbojet combustors operating at simulated rated engine rotor speed. With each combustor the efficiency is very close to 100 percent at sea level and decreases at an accelerating rate as altitude is increased. The general development of turbojet combustors and some important observations on their performance have been described by Whittle (reference 6), Mock (reference 7), Lloyd (reference 8), Watson and Clarke (reference 9), Nerad (reference 10), and Way (reference 11).

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EFFECT OF COMBUSTOR OPERATING VARIABLES

The operating variables that would be expected to affect combustor performance include, of course, the static pressure and temperature of the incoming air. An additional variable, the mixture composition, is expressed herein by the fuel-air ratio, that is, the weight ratio of the total fuel flow to the total air flow. Actual values of the mixture composition vary considerably throughout the combustion space and are probably not directly proportional to the over-all fuel-air ratio. Inasmuch as this fuel-air ratio is the only measurement of mixture composition available from most experimental studies, however, it must suffice herein as an index of the mixture composition. Still another important variable is the velocity of flow of the incoming air. This velocity is roughly inversely proportional to the residence time of the fuel-air mixture in the combustion space, and it is also important in determining heat and mass transfer rates. The velocity of the incoming air is another variable that varies markedly in different parts of the combustion space, so it will be expressed herein by a reference velocity, which is only approximately proportional to actual values of velocity of the air entering the combustion space. This reference velocity is the velocity computed from the total air mass flow rate, the static pressure and temperature at the combustor inlet, and the maximum cross-sectional area of the combustor flow passages. It is the velocity that would exist if the air passed through the maximum cross section of the combustor with a uniform velocity profile and with its density unchanged from the value at the combustor inlet.

<u>Effect of inlet pressure.</u> - The effect of the inlet static pressure on combustion efficiency for constant inlet temperature, constant reference velocity, and constant fuel-air ratio is shown in figure 6 (reference 1). The efficiency decreases at an accelerating rate as the inlet pressure decreases. At high values of inlet pressure the efficiency approaches 100 percent. The data of figure 6 were obtained with an annular combustor of early U. S. design; the inlet temperature was 525° R, the reference velocity was 85 feet per second, and the fuel-air ratio was 0.014. Although the quantitative values of efficiency apply only for this particular combustor operating at the specified conditions, the same general trend of efficiency with variation in inlet pressure has been obtained with a large number of liquid-fuel combustors of both the annular and tubular types. If the combustor design is better or if the constant operating variables of inlet temperature, reference velocity, and fuel-air ratio are more favorable, then the combustion efficiencies will not fall appreciably below 100 percent until pressures well below 10 pounds per square inch

absolute are reached. This fact simply means that for these more favorable conditions the curve of figure 6 has been displaced toward lower pressures; the curve will retain its characteristic shape, 1416 however.

Effect of inlet temperature. - The effect of inlet static temperature on combustion efficiency for constant inlet pressure, constant reference velocity, and constant fuel-air ratio is shown in figure 7 (from reference 1). A decrease in the inlet temperature has an effect analogous to that shown in figure 6 for a decrease in inlet pressure; that is, the efficiency decreases at an accelerating rate as the inlet temperature decreases. The data of figure 7 were obtained with the same combustor as the data of figure 6; the constant reference velocity and fuel-air ratio were the same as for figure 6, and the constant inlet pressure was 13.4 pounds per square inch absolute. Again, the general trend shown by the curve of figure 7 applies to a large number of liquid-fuel combustors over wide ranges of the constant operating variables. Data are presented under "Effect of Fuel Variables" which show the combustor-inlet temperature to have little effect on the combustion efficiency of a vapor-fuel combustor for a range of inlet temperature comparable to that of figure 7. Data are also available for one liquid-fuel combustor that show little effect of inlet temperature for this range of the variables; it is probable that an effect would be observed if lower temperatures could be investigated.

Effect of reference velocity. - The effect of the reference velocity on combustion efficiency for constant inlet pressure, constant inlet temperature, and constant fuel-air ratio is shown in figure 8 (from reference 1). The efficiency decreases at an accelerating rate as the reference velocity increases. These data were obtained with the same combustor as were the data of figures 6 and 7; the constant operating variables were maintained at the values previously noted for figures 6 and 7. Again, the general trend indicated by the curve of figure 8 applies for a large number of combustors over wide ranges of the constant operating variables. With some combustors a decrease in efficiency has been observed at low reference velocities; this decrease may be due to the poor fuel-spray characteristics of the conventional injection nozzles at the attendant very low fuel flow rates.

Effect of fuel-air ratio. - The effect of fuel-air ratio on combustion efficiency for constant inlet pressure, constant inlet temperature, and constant reference velocity is shown in figure 9. Curves are presented for four different combustors because the general trends shown by the curves are somewhat different for various combustors within the range of fuel-air ratios of interest in current aircraft turbine engines. At a fuel-air ratio of 0.017, the efficiency of

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combustor D is substantially constant with changes in fuel-air ratio; the efficiency of combustors E and F decreases with an increase in fuel-air ratio; and the efficiency of combustor G increases with an increase in fuel-air ratio. If the fuel-air ratio for any one of these combustors is varied through a sufficiently wide range, it is probable that the efficiency will follow the general trends shown for combustors E and F; that is, at low fuel-air ratios the efficiency will increase with an increase in fuel-air ratio, at intermediate fuel-air ratios the efficiency will not change appreciably with a change in fuel-air ratio, and at high fuel-air ratios the efficiency will decrease with an increase in fuel-air ratio. The decrease in efficiency at low fuel-air ratios is due to the poor fuel spray developed at low flow rates by conventional fuel injection nozzles, subsequently discussed in the section "Effect of Design Variables." The decrease in efficiency at high fuel-air ratios is believed to be due to overenrichment of the important burning zone at the upstream end of the combustor.

The effect of fuel-air ratio is further illustrated by the curves of figure 10 (from reference 1). Temperature rise through the combustor is plotted against fuel-air ratio in figure 10, and dashed lines of constant combustion efficiency are also indicated. By interpolating between the dashed lines, the efficiency can be estimated for any point on the solid combustor-operating curves. The two solid curves were obtained with the combustor used to obtain the data of figures 6 to 8 operating at two different sets of fixed operating variables of inlet pressure, inlet temperature, and reference velocity. For operation along the upper curve, the inlet pressure was 13.4 pounds per square inch absolute, the inlet temperature was 525° R, and the reference velocity was 85 feet per second; for operation along the lower curve, the inlet pressure was 10.7 pounds per square inch absolute and the inlet temperature and reference velocity were the same as for the upper curve. Inspection of the lower curve shows the general trends previously mentioned, that is, the efficiency is approximately constant at about 74 percent in the intermediate fuel-air ratio range of 0.013 to 0.016, and the efficiency decreases at low and at high fuel-air ratios. The same general trends are also exhibited by the upper curve. The decrease in efficiency with increase in fuel-air ratio at high values of fuel-air ratio is so pronounced for the lower curve in figure 10 that the temperature rise actually begins to decrease with increase in fuel-air ratio. This phenomenon results in a maximum in the curve of temperature rise against fuel-air ratio; that is, there exists a maximum obtainable temperature rise (850° F for the lower curve in fig. 10), that cannot be exceeded with this combustor at these particular operating conditions. This maximum obtainable temperature rise is, of course, an index of the maximum heat release rate that this combustor can achieve at these conditions. At desired flight conditions where the maximum obtainable combustor temperature rise would be below the value required for steady-state engine operation, the engine would be inoperable. It is this phenomenon that results in the altitude operating limits previously noted (fig. 4). 1416

Correlation of effects of inlet pressure, inlet temperature, and reference velocity. - The effects of the operating variables, inlet pressure p_i, inlet temperature T_i, and reference velocity V_r, are such that a correlation results when the combustion efficiency for a given combustor operating with a given fuel over a range of these operating variables is plotted as a function of the parameter $p_i T_i/V_r$. Such correlations of the experimental data obtained with two turbojet combustors are shown in figure 11. This correlation was derived by empirical methods of data analysis. Experimental data obtained with 14 turbojet combustors were plotted in this manner, and in all cases the resulting curve had the same characteristic shape. At high values of the parameter $p_i T_i/V_r$ combustor performance is satisfactory; the combustion efficiency is high and is not very sensitive to changes in operating conditions, as evidenced by the gradual slope of the curves of figure 11. At low values of $p_i T_i/V_r$, however, combustor performance is unsatisfactory; the efficiency is low and decreases rapidly as $p_i T_i/V_r$ decreases. The parameter $p_i T_i/V_r$ does not correct for the effect of fuel-air ratio on efficiency, which accounts for some of the data scatter in figure 11. A correlation such as is shown in figure 11 is very useful because it makes possible a prediction of the combustion efficiency of a combustor for different operating conditions. Also, curves such as these aid in comparing the performance of different combustors from data obtained in unrelated tests.

Explanation of effects of inlet pressure, inlet temperature, and reference velocity. - No explanation has heretofore been given for the variation of combustion efficiency with changes in the operating variables, inlet pressure, inlet temperature, and reference velocity. As previously indicated, if sufficient residence time were allowed the fuel-air mixture in the combustor, then thermodynamic equilibrium would be attained and the efficiency would always be very close to 100 percent provided combustion occurred at all. (Combustion would not occur in a very thin film of the combustible mixture in close proximity to the cold walls of the combustor liner, which would result in some slight loss in efficiency.) The marked decrease in efficiency at adverse operating conditions occurs because the conversion processes, which liberate as sensible enthalpy the chemical energy contained in the fuel, are too slow. These conversion processes include vaporization of the liquid fuel, mixing of the fuel and air, ignition, and oxidation of the fuel to the final products of combustion. The combustion can be visualized as a competition between these conversion processes and the quenching that occurs when the reacting mixture is swept out of the burning zone and diluted with cold air and when the mixture comes in contact with the relatively cool walls of the combustor liner. Because of the obvious complexity of the over-all process, no exact theoretical treatment is possible. If the rate of any one of the conversion processes is substantially less than the rates of the others, however, this one process will govern the over-all rate and hence will determine the combustion efficiency. As one possible explanation for the loss in combustion efficiency, a theoretical analysis was made with the simplifying assumption that the chemical reaction (the oxidation of the fuel) constitutes an over-all rate-determining step in the chain of conversion processes. This analysis served to predict the correlation effected by the parameter $p_i T_i/V_r$ and also predicted the shape of the curves of figure 11. Thus the effects on combustion efficiency of the inlet pressure, inlet temperature, and reference velocity may be the result of their effect on the rate of the chemical reaction. These variables affect the collision frequency of the reacting molecules and also determine the residence time of the reacting mixture within the combustor.

Summary of effect of operating variables. - The combustion efficiency of turbojet combustors decreases at an accelerating rate with a decrease in the combustor-inlet pressure or temperature and with an increase in the combustor reference velocity; combustion efficiency can be correlated with these variables as a function of the parameter $p_i T_i/V_r$. The effect of fuel-air ratio on combustion efficiency is largely dependent upon the atomization characteristics of the fuel-injection system, and as such will be discussed more completely in a subsequent section of this paper.

EFFECT OF DESIGN VARIABLES

The general trends discussed in the preceding section are essentially the same for the various turbojet combustors. The absolute values of efficiency and obtainable temperature rise for given operating conditions vary, however, with the combustor design. Good design must favor the conversion processes of combustion over the combustion-terminating processes. The significant design factors for high combustion efficiency would be apparent if the exact contribution of each process to combustor performance were known. Such, however, is not the case. Further, compromises to meet the many combustor requirements as enumerated in the "Introduction" must be included in any design.

Several design variables have been investigated by the NACA for their effect on combustion efficiency and obtainable temperature rise. They are combustor size and shape; total open area, distribution, size, and shape of air-admission holes in the walls of the combustor liner; and fuel-injection methods. An examination of the trends observed with these variables assists in understanding the part played by each of the individual processes that contribute to combustion efficiency.

Combustor size. - Concerning combustor size, the combustor must have a sufficiently high heat release rate to meet the power requirements of the engine. This requirement introduces the immediate question of whether combustor volume is the single limiting factor in altitude operation. Partly to answer this question, a simple diffusion flame of propane in air was burned at reduced pressures (fig. 12) and the volume required to effect a given rate of heat release per unit time determined from photographic measurements of the reaction zone volume (reference 12). The volume in cubic inches required to release 1000 Btu per hour, computed in this way, is plotted against pressure in figure 13. At pressures above 120 millimeters, the reaction zone of the flame was too thin to allow estimates to be made of its volume, although the curve extrapolates reasonably well to a value corresponding to 7×10^8 Btu per hour per cubic foot at 1 atmosphere, a value cited in reference 10 and based on an estimate of flame thickness for a flame propagating in a tube at a known rate.

Also shown in figure 13 is the volume available for the same heat release rate in a turbojet combustor at the design fuel flow rates and assuming 100-percent combustion efficiency. It is noted that the combustor affords sufficient volume for the flame alone, although the volume required increases from less than 1 percent of that available to 5 percent of the combustor at about 60,000 feet for the combustor heat release rates currently used.

In another experiment, a wick lamp was substituted for the propane flame (reference 12) in similar apparatus and the entire apparatus was immersed in a calorimeter so that combustion efficiency could be measured. The results are shown in figure 14 and are compared with the same turbojet combustor. The diffusion flame burned at 100-percent efficiency down to the blow-out limit. Apparently a flame will burn efficiently at pressures much lower than those now being used if given the right environment in the combustor.

A further consideration of combustor size may be made by examining the reference velocity. Figure 15 shows the effect on combustion efficiency as the air-flow rate through a unit cross-sectional area of a typical combustor is increased. The trend is similar to that previously discussed for figure 8. The combustor-inlet conditions are 15 pounds per square inch and 620° R. This combination of inlet-air pressure and temperature represents a turbojet engine with a 4:1 compression ratio operating at full rotational speed at 500 miles per hour at an altitude of 40,000 feet. The curves representing constant combustion efficiency show a regular decrease in efficiency as reference velocity is increased. Operation of this combustor at efficiencies of 90 percent or greater, over a reasonable temperature range, is achieved at air flows less than those indicated by the 90-percent curve. A similar plot for four different combustors but with only the 90-percent combustion efficiency curve is shown in figure 16. Combustor M was used in the preceding figure. Combustor J was limited at high air flows by blow-out. At low air flows or low fuel flows (low temperature rise), J was limited by decreasing combustion efficiency because this combustor, unlike the other three, had a fixed-orifice fuel nozzle. An examination of these and similar data for other, different combustor designs indicates that a reasonable design figure for combustion in the 90- to 100-percent efficiency range for the inlet conditions shown is 5 pounds of air per second per square foot of maximum cross-sectional area of combustor. These inlet conditions correspond to a reference velocity of about 75 feet per second. Similar data at other altitude operating conditions, such as the higher pressure and temperature of 25 pounds per square inch absolute and 710° R and at the lower pressure and temperature of 10 pounds per square inch absolute and 550° R, also indicate a good design velocity at altitude to be about 75 feet per second. This velocity is indicated with present combustor designs. Use of smaller dimensions for the maximum combustor cross-sectional area, or higher velocities, may be expected to increase the difficulty of achieving high combustion efficiency at altitude.

Design of primary zone. - A most important design consideration for stable and efficient combustion is, of course, the primary combustion zone, where that portion of the air that is to burn the fuel should be admixed. This zone is where low velocities and reverse flows afford sufficient residence time for initiation of flame and "piloting", as has been shown in visual studies (reference 11).

Some important design considerations for the primary zone appear in figure 17, where combustion efficiency at simulated full engine speed is plotted against grades of altitude. The four combustors were of the annular type and were designed to fit into the same housing. Each of the sketches represents an element of surface from the combustor liner and contains one of the longitudinal rows of air admission holes. Also shown are longitudinal cross-sectional views of the upstream end of the combustor liner, showing the fuel nozzles and the relative size of the combustion zones. Combustors N, O, and P were of the double annular type; that is, each of these combustors had two concentric annular combustion zones. Combustor Q was a single-annulus combustor. Combustors N and O were alike in all respects except that combustor O had wider combustion zones. Combustor O exhibits higher combustion efficiency at all altitudes than combustor N. Combustor Q differed from combustors N and O in two respects; first it had one large combustion zone rather than two small ones; and second, it had long narrow slots in the liner rather than circular holes. Combustor Q surpasses combustors N and O in efficiency at all altitudes. The principal reason for the better performance of combustor Q is believed to be the difference in the width of the combustion zone rather than the difference in shape in the liner perforations. This reason is concluded from data obtained in another investigation carried out with a combustor similar to combustor Q. In this combustor, the liner perforations were changed from circular holes to long, narrow slots without modifying the width of the combustion zone, and no substantial improvement in combustion efficiency was noted. Thus, comparison of the efficiencies for combustors N, O, and Q shows the progressive improvement in combustion resulting from a progressive increase in the width of the upstream end of the combustor liner. Possible reasons for this improvement are that: (1) A smaller portion of the fuel spray impinges on the wall; (2) lower local velocities are provided; (3) a larger quantity of material burns in the low-velocity region of the combustor; and (4) quenching of chemical reactions by the cold walls is reduced. In this latter connection, it is significant to recall figure 13 in which the volume of a diffusion flame is shown to increase as pressure decreases.

The altitude operating limits for these combustors are designated by a symbol at the end of each curve. It is seen that these limits are in the same order as the efficiencies.

Comparison of the combustion efficiencies and operating limits of combustors O and P shows the effect of changing the distribution of open area along the length of the combustor liner. These two combustors were identical in all respects except for this distribution of the open area. It is seen that a distribution of open area that allows less air into the upstream end or burning zone combustor P, is to be preferred over the area distribution shown for combustor O.

In order to determine the criteria for optimum size and distribution of the openings in the liner wall, systematic investigations were made in several different annular turbojet combustors both of proprietary manufacture and of NACA design. Some results from one of these studies are presented in figure 18 as representative of the findings. The combustion efficiencies of four different configurations of an annular combustor are compared at each of four different operating conditions. Again the sketches in the lower part of the figure show an element of surface from the combustor liner; the smaller holes are at the fuel-nozzle end. The total open area of the holes in the combustor liners is indicated. The combustors with smaller holes have higher pressure loss, of course. It is noted that combustor U is better than combustor S of like open area but different air distribution, and, similarly, combustor T surpasses R. Also, combustors U and T are generally superior to both R and S, thus clearly indicating the importance of the distribution of the secondary air. It is also noted that the effect of increasing the pressure drop was to increase combustion efficiency; combustor S has higher efficiencies than R, U higher than T; this trend with pressure drop is not universally found, however.

This and other research have indicated that for good altitude limits and combustion efficiencies with combustors of the general type described, the first 20 to 25 percent of the open area in the liner wall should be gradually achieved over a distance of about 8 to 10 inches or more from the upstream end of the liner; this may be one-half or more of the length of many combustors. This gradual admission of air aids in assuring that over a range of fuel flows, especially at low fuel flows such as at high altitude, correct mixtures for combustion will exist in the upstream end of the combustor.

Pressure loss, as such, in the combustor for the purpose of generating turbulence and mixing appears to be subordinate in importance to the factors just discussed as long as reasonable values of pressure loss are maintained. Pressure loss of 10 times a reference dynamic pressure based on inlet-air density and weight flow and the maximum cross-sectional area of the combustor is suggested as a reasonable value. It is how the pressure loss is used, that is, how and where the air is directed in the combustor, that is important.

Fuel injection. - If satisfactory combustion requires the existence of localized fuel-air ratios that are at or near stoichiometric in the primary zone for all combinations of engine speed and altitude, then the manner in which the fuel is admitted to the combustor can be expected to be fully as important as the manner in which air is admitted. Important variables are the configuration of the spray because it influences distribution and mixing of the fuel, and injection pressure because it affects drop-size distribution as well as the distribution and mixing of the fuel.

The influence of fuel-spray configuration on combustion efficiency is illustrated in figure 19, which shows the combustion efficiency of a tubular combustor plotted against fuel flow rate for two types of spray nozzle using kerosene-type fuel (reference 13). The data for the lower curve were obtained with a hollow-cone fixed-orifice-type fuel nozzle. A loss in efficiency accompanies the collapse of the spray cone at low fuel flows with this nozzle. The data for the upper curve were obtained with a conventional nozzle to which had been added a small divergent section at the exit of the fuel orifice. At low rates of fuel flow, the fuel appears to follow the divergent cone and forms a wide angle spray as shown in figure 19. The combustion efficiencies obtained with the modified nozzle clearly indicate that large improvements in combustion efficiency can be achieved by the use of a nozzle that maintains a preferred fuel-spray configuration, especially at low fuel flows such as are encountered at high altitude.

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The effects of fuel-injection pressure on combustor performance have been studied by using fuel nozzles of different rated capacities (rated at 100 lb/sq in. fuel pressure) in order to vary the injection pressure. Some of the trends are illustrated in figure 20, a plot of combustion efficiency against combustor temperature rise for an annular combustor operated on gasoline at fixed inlet-air conditions. The operating conditions were deliberately selected to give marginal operation for this combustor. The data indicate that the 3-gallon-per-hour nozzle gave the highest combustion efficiency at low values of temperature rise, with the 7.5-gallon-per-hour and the 10.5-gallon-per-hour nozzles giving higher combustion efficiencies at higher values of temperature rise. The higher the injection pressure, the lower were the temperature-rise limits encountered, however. This trend is further illustrated in figure 21 where the data of figure 20 with results for additional fuel nozzles included are plotted as combustion efficiency against combustor temperature rise for different values of fuel-injection pressure differential. From these and other similar data it may be concluded that at severe operating conditions increased fuel-injection pressure aids combustion efficiency at low fuel flows; but that it is possible to atomize the fuel too well and to reach a condition where additional fuel gives no additional heat release in the combustor. The combustor was designed for gasoline and 10.5-gallon-per-hour nozzles. Apparently the fine atomization and rapid vaporization with the small nozzles caused a fuel-air mixture in the primary zone that was too rich to burn at higher fuel flows.

An attempt was made to study the individual effects on combustor performance of fuel atomization, vaporization, and distribution in another investigation. In this research a tubular combustor was operated with two fuels, JP-1 (a kerosene-type fuel) and gaseous propane. Comparison between the performance of the fuels isolated the effects of atomization and vaporization. The third function, mixing, was studied by injecting the propane as a single low-velocity stream along the longitudinal axis of the combustor, and as many high velocity streams distributed uniformly across the upstream end of the combustor. Some of the results of this research are indicated in figures 22 and 23. In figure 22, a plot of combustion efficiency against combustor inlet-air temperature for the three injection schemes, it is seen that combustion efficiency with propane is less affected by a decrease in inlet temperature. This result may be because the temperature effects on atomization and vaporization rates are not present. In figure 23, the curves line up in the same order when pressure is the variable as they did when temperature was the variable in the preceding figure. The multiport injection of propane consistently gave the highest efficiencies, indicating the importance of mixing of fuel and air as well as the importance of eliminating atomization and vaporization. The effect of decreased pressure and temperature on combustion efficiency with propane and the multiport injection may also be contrasted to the trends in figures 6 and 7. From evidence of this type, it has been concluded that when the functions of atomization and vaporization are eliminated and when mixing is good, combustion efficiencies are much less influenced by the decreased inlet pressures and temperatures corresponding to high-altitude operation. Figure 14 also indicates that this should be so with regard to pressure. Thus the data obtained further indicate the necessity of controlling the local fuel-air ratio in the primary zone of the combustor. It was also apparent in this research that not all the depreciation in combustion efficiency at altitude could be ascribed solely to the fuel-preparation processes.

From the research on fuel injection completed, it is concluded that it is necessary that the characteristics of the fuel spray should not vary too widely over all operating conditions. This conclusion is a corollary to the concept that the fixed geometry of the liner is intended to provide gradual admission of air so that correct mixtures can be established in the upstream, or low-velocity end of the combustor at any operating condition. A fuel nozzle that will maintain satisfactory injection pressures over a wide range of fuel flows is indicated from the studies.

EFFECT OF FUEL VARIABLES

The preceding discussion has indicated the need of adequate control, at all conditions of operation, of the fuel-air mixture in the combustion zone. It has been shown that the design of the turbojet combustor has been directed toward such control by proper choice of the air admission and fuel-injection-system design. If it is assumed that the combustion process occurs in the vapor phase, a final control of the fuel-air mixture must depend on the vaporization properties of the fuel. Further, the combustion process itself, even at optimum fuel-air mixture conditions, would be expected to be influenced by certain combustion characteristics relating to the composition of the fuel, such as flame speed or ignition temperature.

At conditions favorable for combustion it has been seen that combustor efficiency may be relatively insensitive to changes in operation and design variables; similarly, under such conditions, satisfactory combustor efficiency may be obtained with fuels of widely varying properties. At adverse conditions of operation, however, there are significant effects of fuel properties on combustor efficiency. Three typical hydrocarbon-fuel mixtures, varying both in volatility and in composition, are shown in the following table:

Fuel	Boiling range (°F)	Composition (percent by volume)	
		Aromatics	Paraffins, cycloparaffins
Aviation gasoline (AN-F-28)	104-328	14	86
Kerosene type (AN-F-32)	314-480	11	89
Diesel oil	364-664	19	81

Aviation gasoline represents a typical reciprocating engine fuel, which has been used in some turbojet engines; kerosene, an early turbojet engine fuel; and Diesel oil, the less-volatile components of petroleum, which could be utilized in turbojet engines. The combustion-efficiency performance of the three fuels in an annular combustor is shown in figure 24. These data illustrate the typical trend of combustion efficiency with simulated-flight altitude, which has been observed with many fuels in many different combustors. The actual values of combustion efficiency would, of course, depend upon the design factors and upon the operating conditions. The data indicate that the combustion efficiencies of these fuels tend to converge, near 100-percent combustion efficiency. As altitude is increased, the combustion efficiencies begin to decrease rapidly, and significant differences in combustion efficiency among the fuels are observed. It appears that the least volatile fuel, Diesel oil, burns with the lowest combustion efficiency, and the most volatile fuel, aviation gasoline, burns with the highest combustion efficiency. In other words, the fuel used affects the combustion efficiency at altitude.

The trend of combustion efficiency with fuel volatility noted in figure 24 has been observed in other combustor types. Tests with several fuels in a single tubular combustor at adverse operating conditions (inlet-air pressure, 6 lb/sq in. abs.; inlet-air temperature, 75° F; reference velocity, 111 ft/sec) indicated a linear relation between combustion efficiency and volumetric average boiling temperature, as shown in figure 25, (from reference 14). The combustion efficiency decreased with an increase in volumetric average boiling temperature. The effect of one additional fuel property, composition, is also indicated in this figure; the aromatic-type fuels, benzene and xylene, gave lower combustion efficiencies than did the other types of hydrocarbon of the same volatility.

The effect of hydrocarbon composition on combustion efficiency has been further investigated in another tubular combustor with pure hydrocarbons. Figure 26 presents combustion-efficiency data for four pure paraffinic hydrocarbons tested over a wide range of reference velocities at adverse conditions of combustor inlet-air pressure (7 lb/sq in. abs.) and inlet-air temperature (40° F). The first two fuels, n-heptane and isooctane, have identical boiling temperatures and hence vary only in hydrocarbon structure, representing a straight-chain paraffin and a branched-chain paraffin, respectively. The n-hexane and 2,3-dimethylbutane have almost equivalent boiling temperatures and vary, similarly, in structure, again representing a straight-chain and a branched-chain paraffinic hydrocarbon, respectively. In both cases the straight-chain paraffin operated with higher combustion efficiencies than did the branched-chain paraffin.

Two fuel characteristics, either or both of which may account for the effect of fuel structure on combustion efficiency, are indicated in figure 26: fundamental flame velocity (reference 4) and spontaneous ignition temperature. Comparisons of the fundamental flame speeds of these fuels indicate that higher combustion efficiencies are observed with fuels having higher flame velocities. These same fuels also have the lower spontaneous ignition temperatures, however, thus the relative importance of the two fuel characteristics in determining the combustion-efficiency performance of a fuel cannot be ascertained from these data. Current research is being directed toward the correlation of these and other fuel characteristics with combustor performance.

The trends that have been determined can be applied to many combustors and many combustor operating conditions. Exceptions do exist, however, and the relative combustion efficiencies of fuels are frequently altered by a different choice of combustor design or operating condition. As an illustration, there is plotted in figure 27 the variation of combustion efficiency with combustor temperature rise for two fuels, gasoline and Diesel oil, and two combustor inlet-air temperatures. With a combustor inlet-air temperature of 240° F, the more volatile gasoline gave higher combustion efficiencies throughout the range of combustor temperature rise. When the inlet-air temperature was reduced to 150° F, however, the gasoline gave a maximum combustion efficiency at a temperature rise of about 1200° F. As the fuel-flow rate to the combustor was increased in an attempt to obtain higher values of combustor temperature rise, a rapid decrease in the combustion efficiency of gasoline occurred. This decrease was followed by a marked reduction in obtainable temperature rise, and finally, by flame blow-out. The occurrence of limiting values of combustor temperature rise, accompanied by decreases in combustion efficiency, has been attributed to the presence of over-rich fuel-air mixtures in the primary combustion zone. This condition will be encountered then at the high fuel-flow rate accompanying high temperature rise operation and with a more volatile fuel (fig. 27(a), gasoline).

A similar explanation has been applied to trends of combustion efficiency with varying fuel-injection-nozzle characteristics, as previously discussed. Data illustrating the variation of combustion efficiency with combustor temperature rise for two fuels, gasoline and Diesel oil, are compared for operation with two different fuel-injection systems (3.0 and 10.5-gal/hr nozzles) in figure 28. With the larger fuel-injection nozzles, higher combustion efficiency performance was obtained with the more volatile fuel, gasoline. With the smaller nozzle, however, the over-rich mixture conditions, provided by the improved atomization characteristics, resulted in better performance with the less volatile fuel, Diesel oil. It should be noted, however, that even the improved combustion efficiency of Diesel oil with the smaller nozzles did not quite equal the improved combustion efficiency of gasoline with the larger nozzles, indicating that optimum fuel-injection conditions will not necessarily eliminate the effect of fuel properties on combustion efficiency.

It should not be inferred from the preceding discussion that volatility and hydrocarbon composition, or structure, are the only fuel variables that may have an effect on combustion efficiency in a turbojet combustor. The effects of these particular variables have been investigated more intensively (reference 14). Other variables such as viscosity and surface tension may also affect the combustion efficiency, for example, by affecting the fuel-atomization characteristics.

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It may be concluded that certain fuel properties significantly affect the combustion efficiency of a combustor at adverse conditions of operation. The trends that have been determined indicate that: (1) Combustion efficiency increases with an increase in fuel volatility; (2) lower combustion efficiencies are observed with aromatic-type fuels than with other hydrocarbon-type fuels; and (3) straight-chain paraffins operate with higher combustion efficiencies than do branched-chain paraffins. Considerations of fuel availability and of other turbojet performance factors obviously require certain compromises to obtain the optimum combination of fuel and combustor design.

CONCLUDING REMARKS

In conclusion, the research data reviewed herein have shown that as the environment of the combustor becomes one of low pressure and low temperature at high altitude, low combustion efficiencies and limited values of obtainable temperature rise are encountered. Systematic research on combustors and fuels and comparison of the results with results from basic studies have led to at least a qualitative understanding of what is required for successful combustor performance. The necessary criteria for achieving stability of operation and high combustion efficiency over a wide range of operating conditions are: (1) that localized fuel and air mixtures having fuel-air ratios at or near stoichiometric values exist somewhere in the combustor; (2) that these localized mixtures of correct composition exist sufficiently long for ignition and combustion to occur; and (3) that all the fuel entering the combustor be involved in just this manner.

With regard to the operating environment of the combustor, the trend to higher-pressure-ratio gas-turbine engines should aid in promoting good combustion efficiency at high altitude. Lower combustor inlet-air velocities can be achieved by more complete use of the space available on the engine or its installation. This reduction in velocity is an attempt to increase residence time of the fuel and could also be achieved by longer combustors. Some other design features that aid in establishing the criteria previously described include a wide upstream end, or primary zone, gradual admission of the primary air, and variable-flow fuel nozzles. It has been observed that it is necessary to match the combustor design, the fuel nozzles, and the fuel to insure satisfactory fuel-air ratios in the primary zone at

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all operating conditions. Fuels that burn faster or ignite at lower temperatures or both should alleviate the combustion-efficiency problem, although appreciable changes in this regard may jeopardize the fuel-supply problem.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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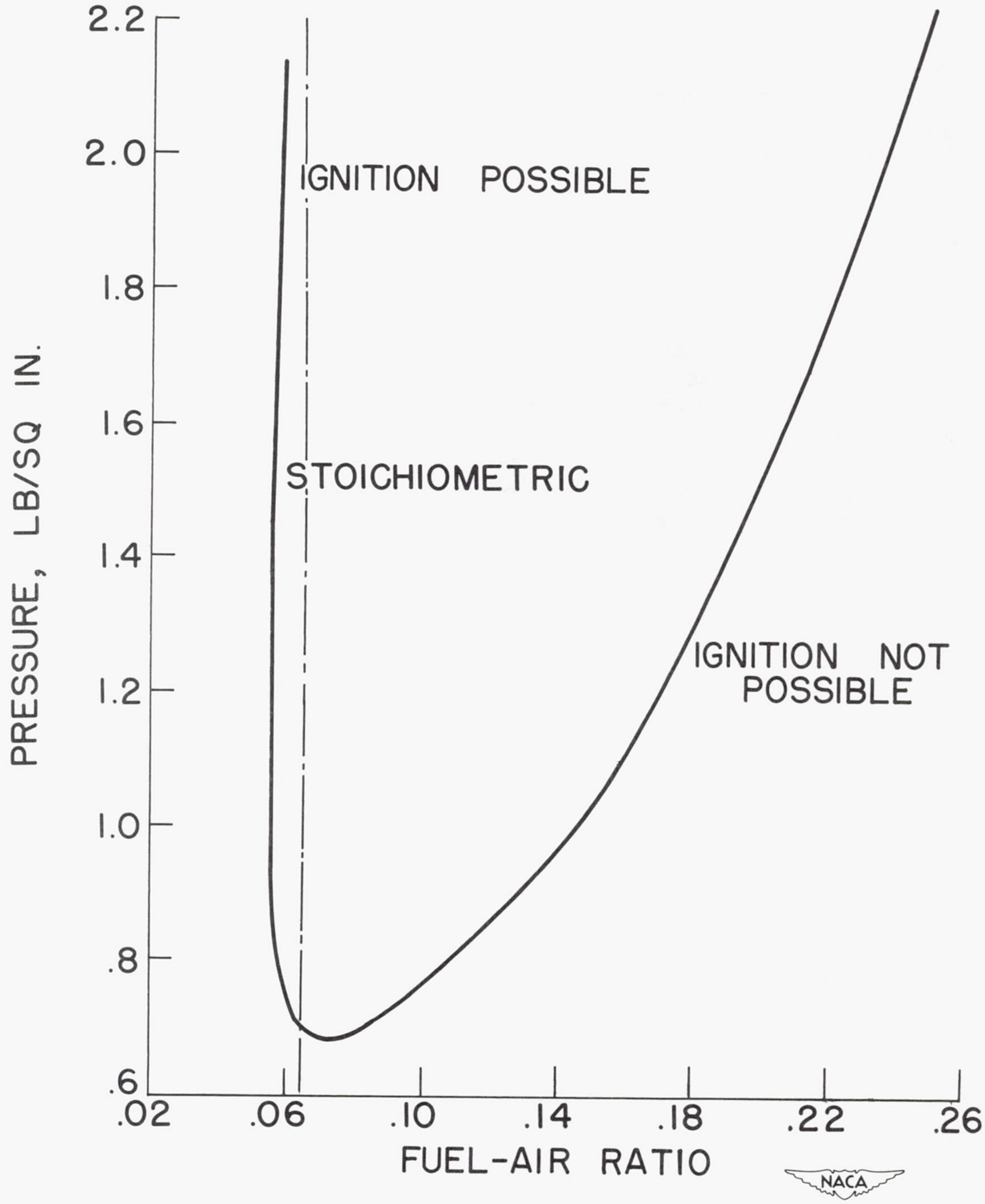

Figure 1. - Inflammability limits of gasoline-air mixtures.

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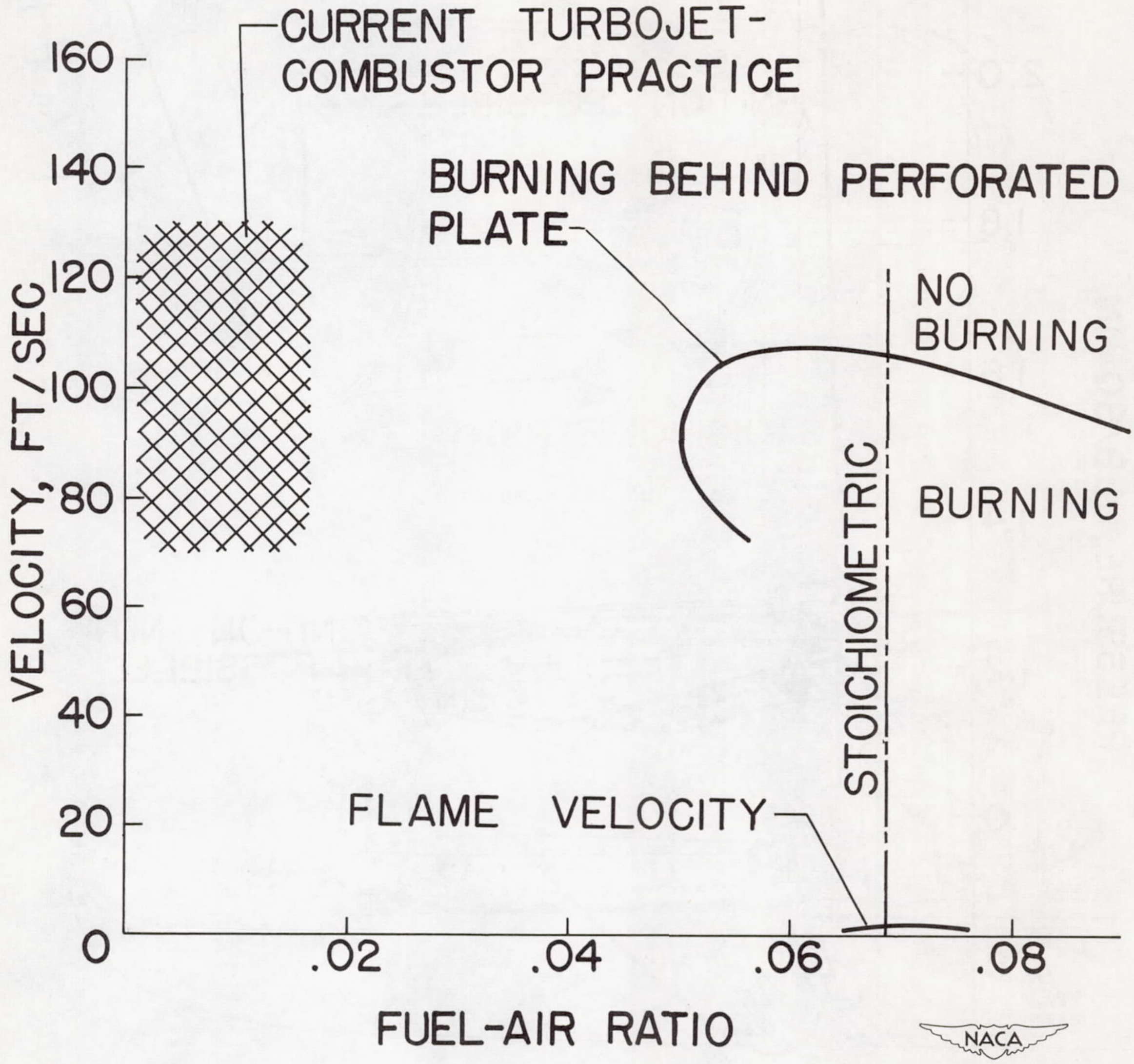
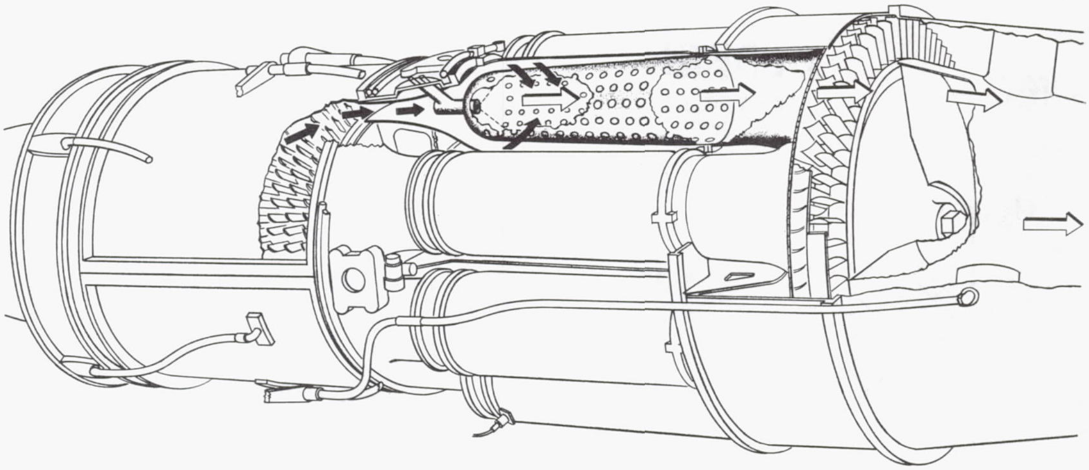
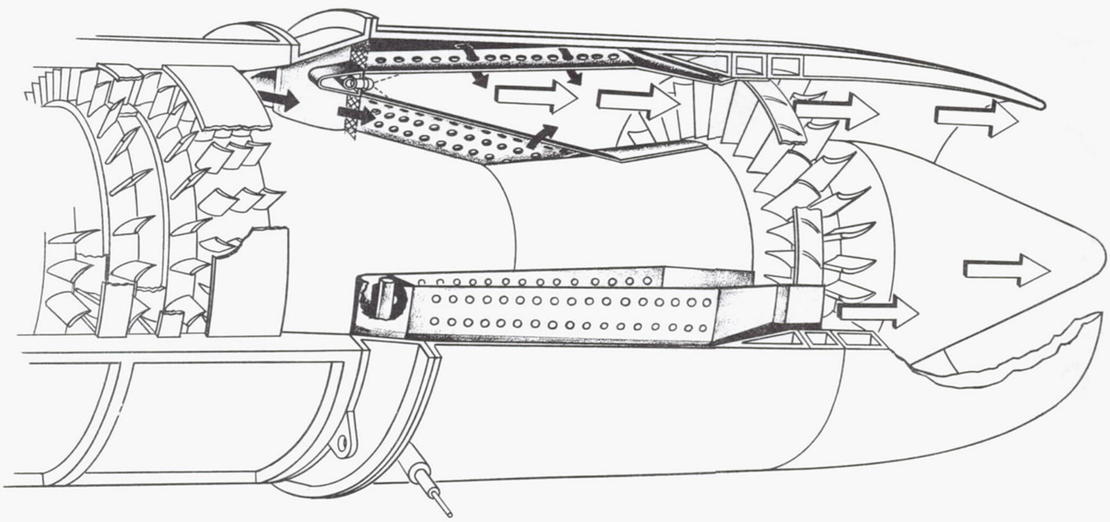


Figure 2. - Combustion limits.



(a) Tubular combustor.



(b) Annular combustor.

Figure 3. - Cutaway drawings of turbojet engines showing the combustors.

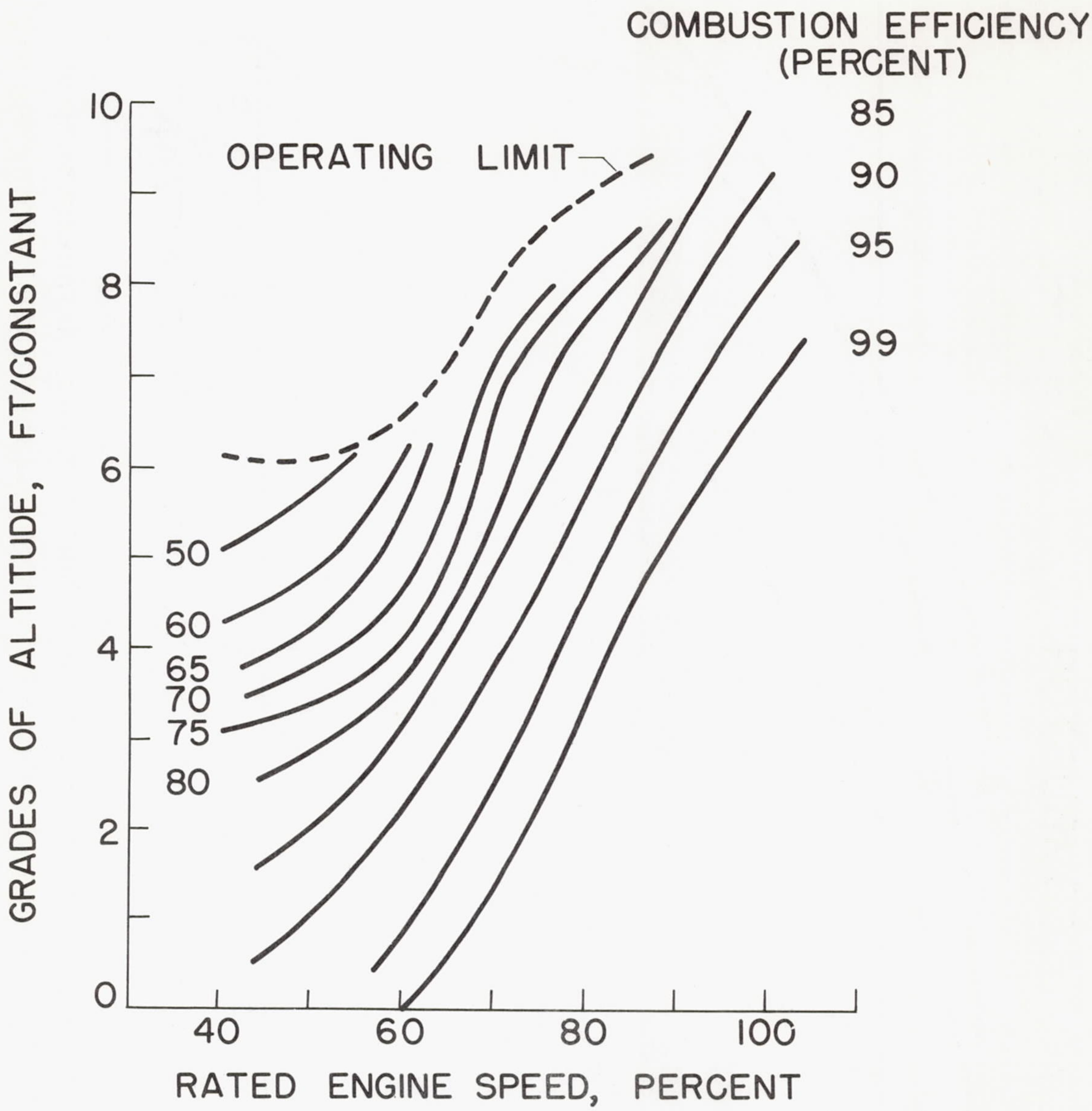


Figure 4. - Combustion efficiencies and altitude operating limits of a turbojet combustor at various simulated flight conditions.

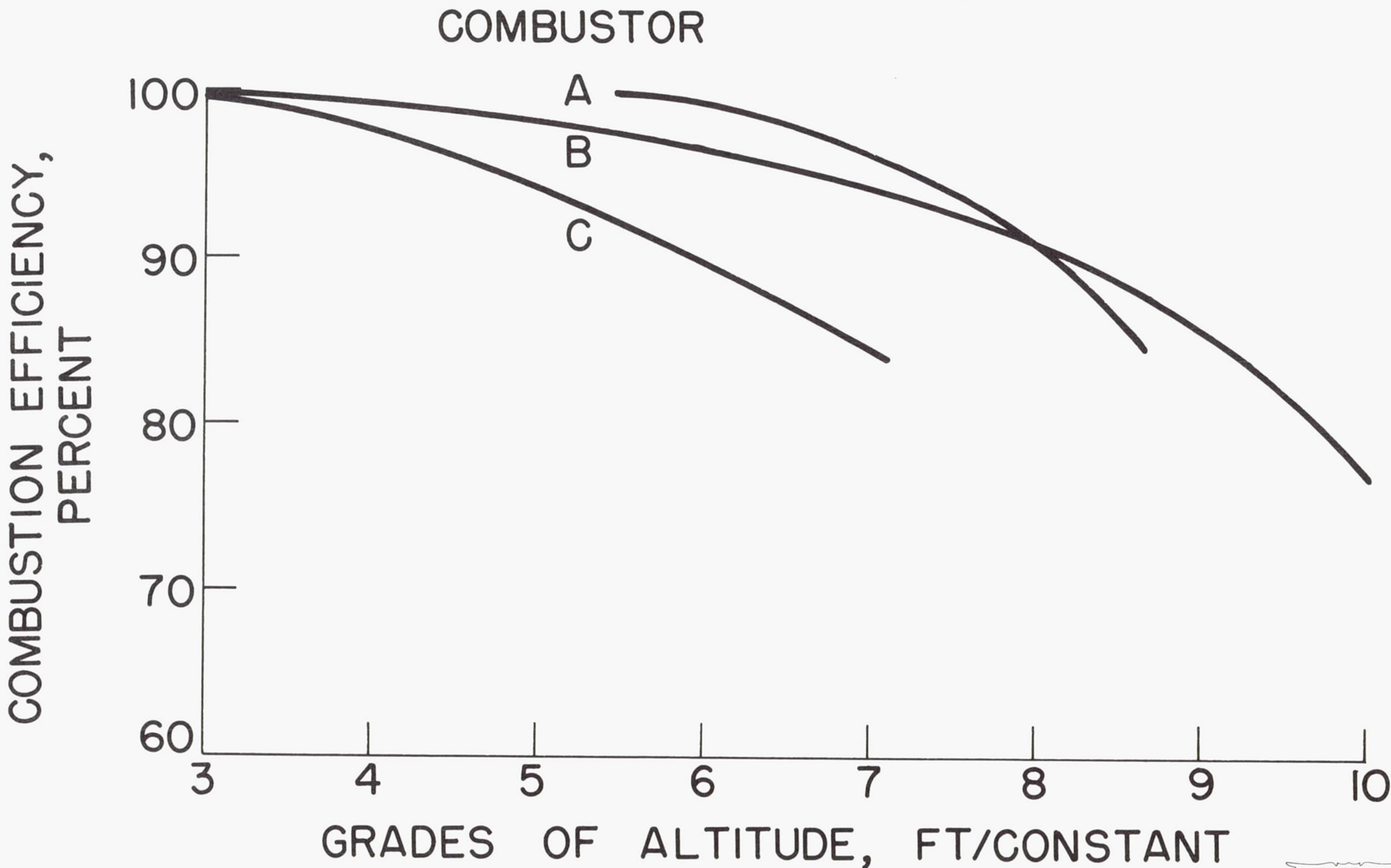


Figure 5. - Effect of simulated flight altitude on combustion efficiency of three turbojet combustors at simulated rated engine speed.

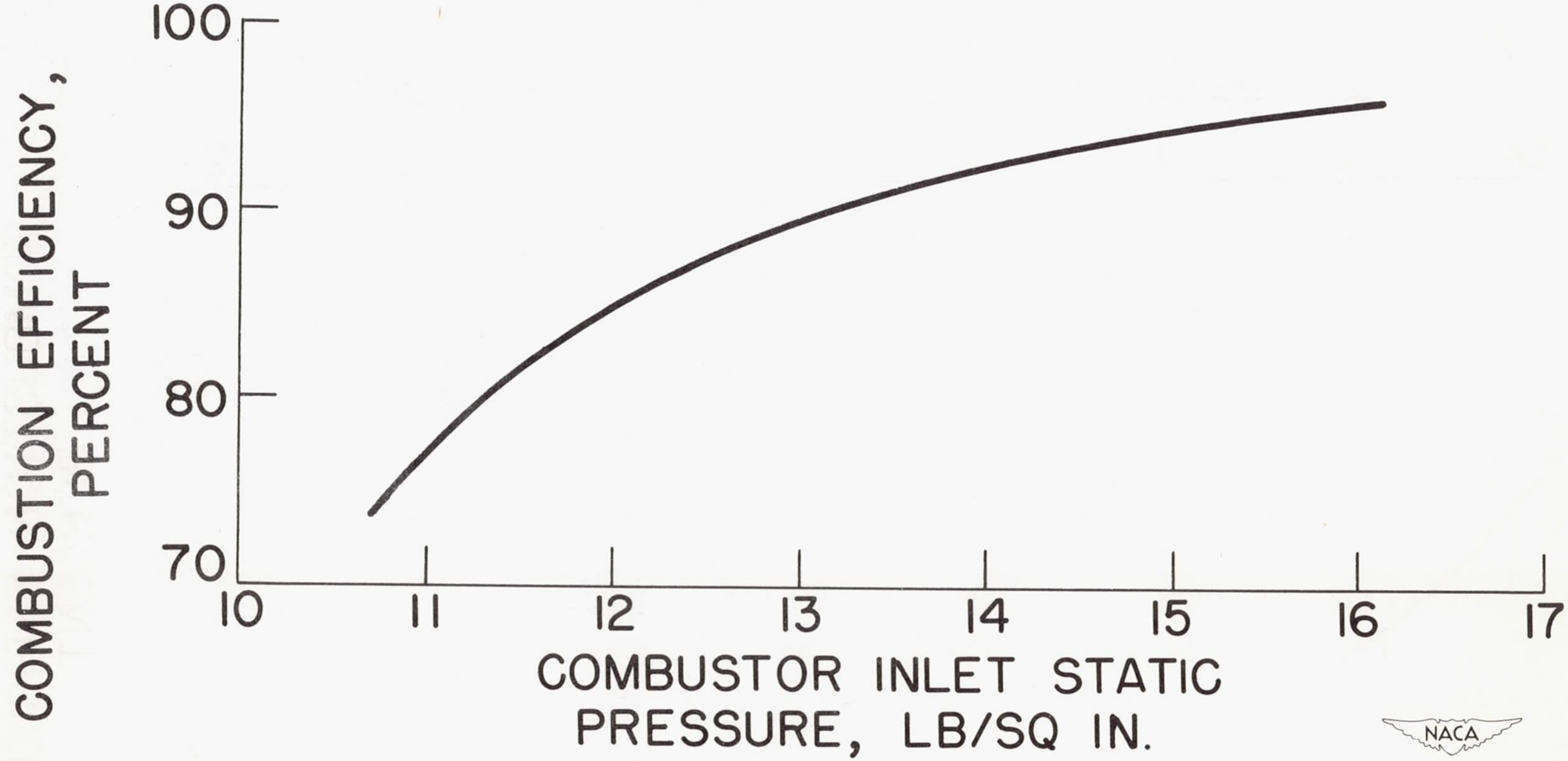


Figure 6. - Effect of combustor inlet static pressure on combustion efficiency at constant inlet temperature (525° R), constant reference velocity (85 ft/sec), and constant fuel-air ratio (0.014).

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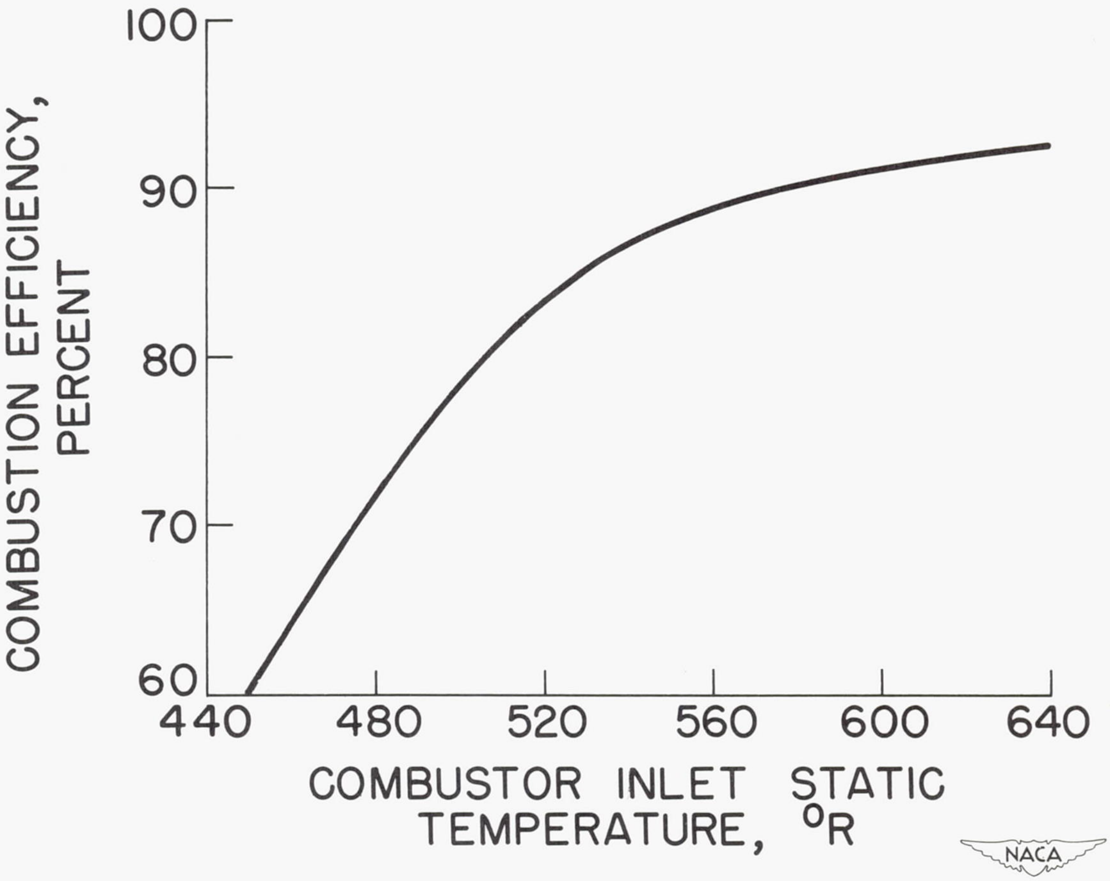

Figure 7. - Effect of combustor inlet static temperature on combustion efficiency at constant inlet static pressure (13.4 lb/sq in.), constant reference velocity (85 ft/sec), and constant fuel-air ratio (0.014).

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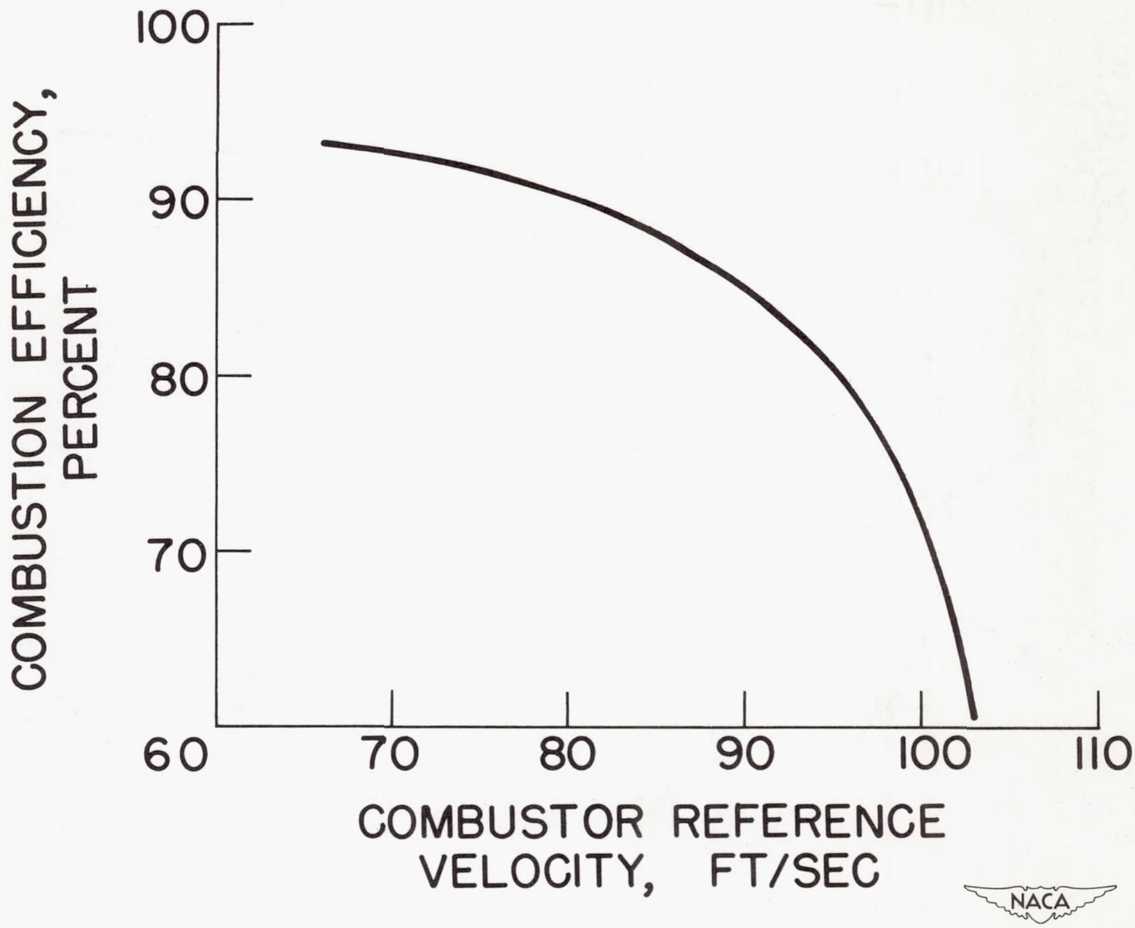

Figure 8. - Effect of combustor reference velocity on combustion efficiency at constant inlet static pressure (13.4 lb/sq in.), constant inlet static temperature (525° R), and constant fuel-air ratio (0.014).

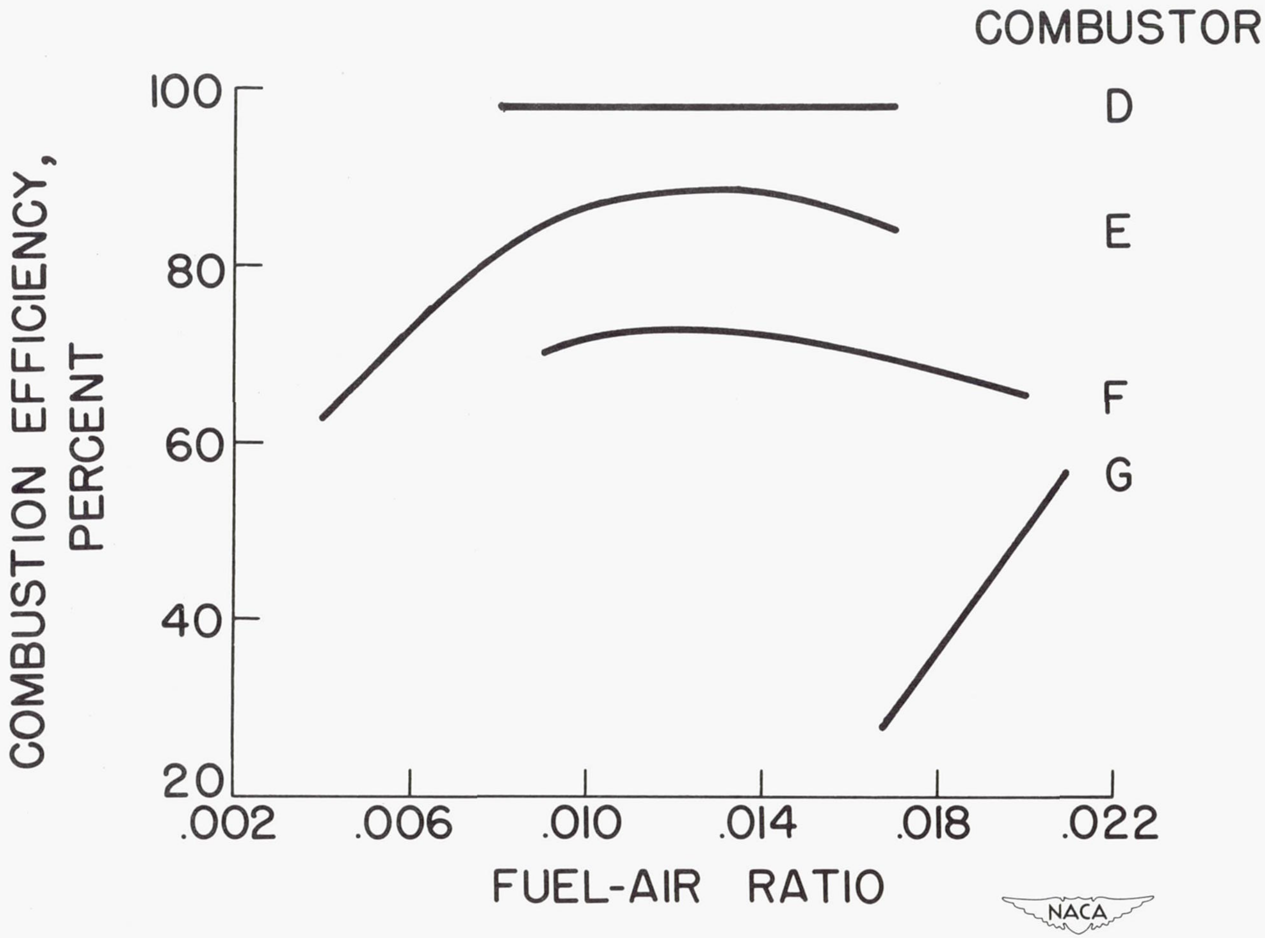

Figure 9. - Effect of fuel-air ratio on combustion efficiency of four turbojet combustors at constant inlet pressure, constant inlet temperature, and constant reference velocity.

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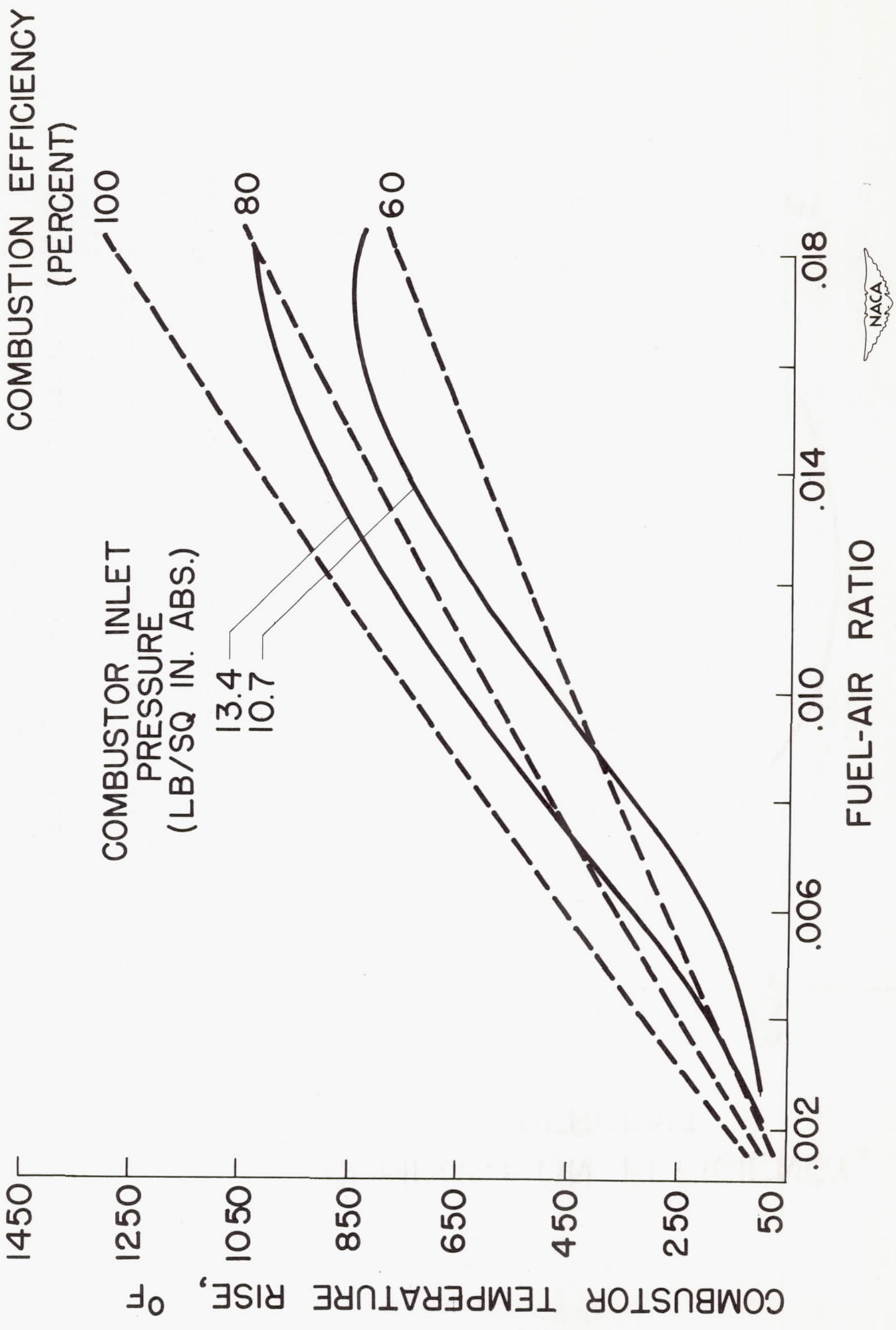
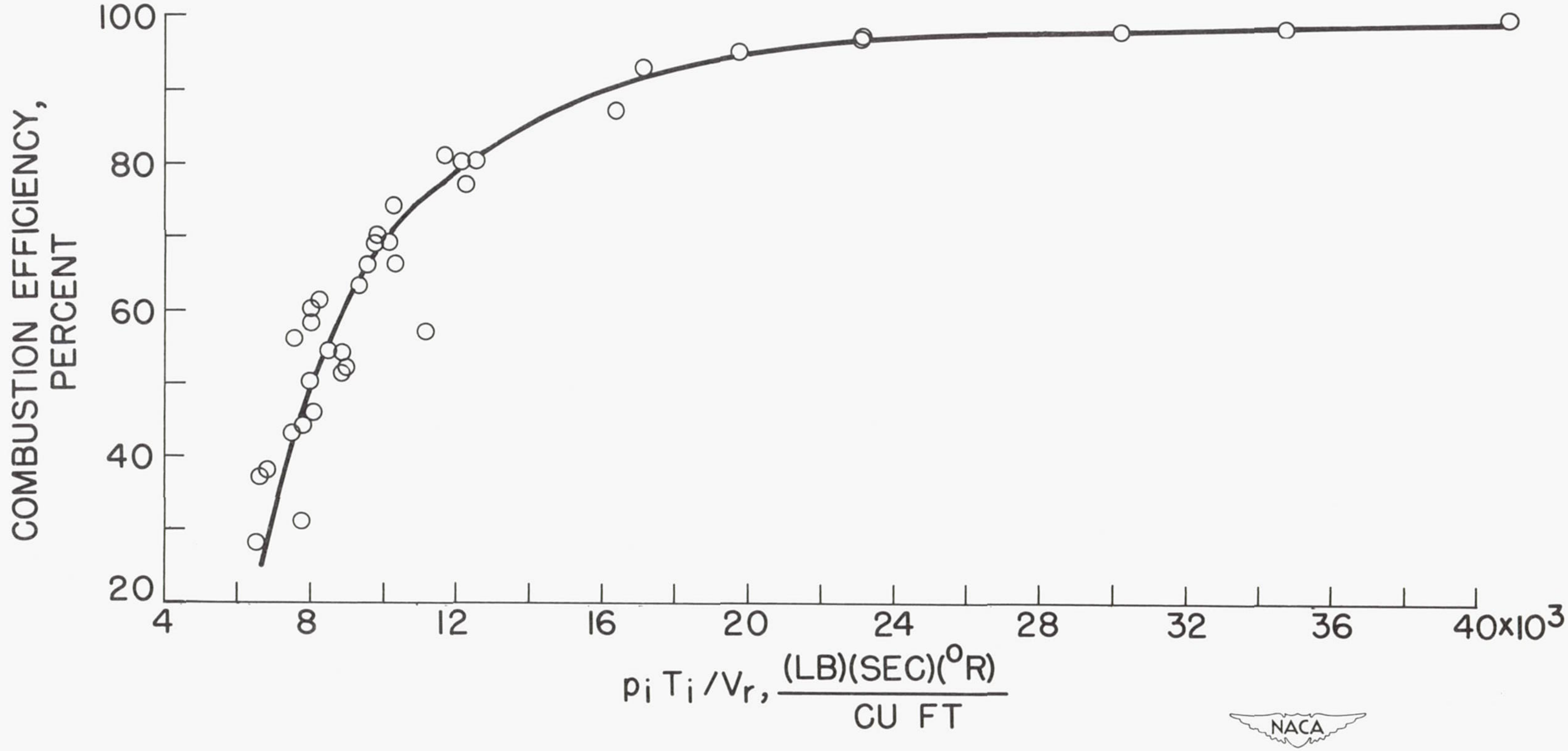


Figure 10. - Effect of fuel-air ratio on temperature rise through combustor at constant inlet pressure (13.4 and 10.7 lb/sq in.), constant inlet temperature (525° R), and constant reference velocity (85 ft/sec).



(a) Combustor H.

Figure 11. - Correlation of combustion efficiencies at different operating conditions.

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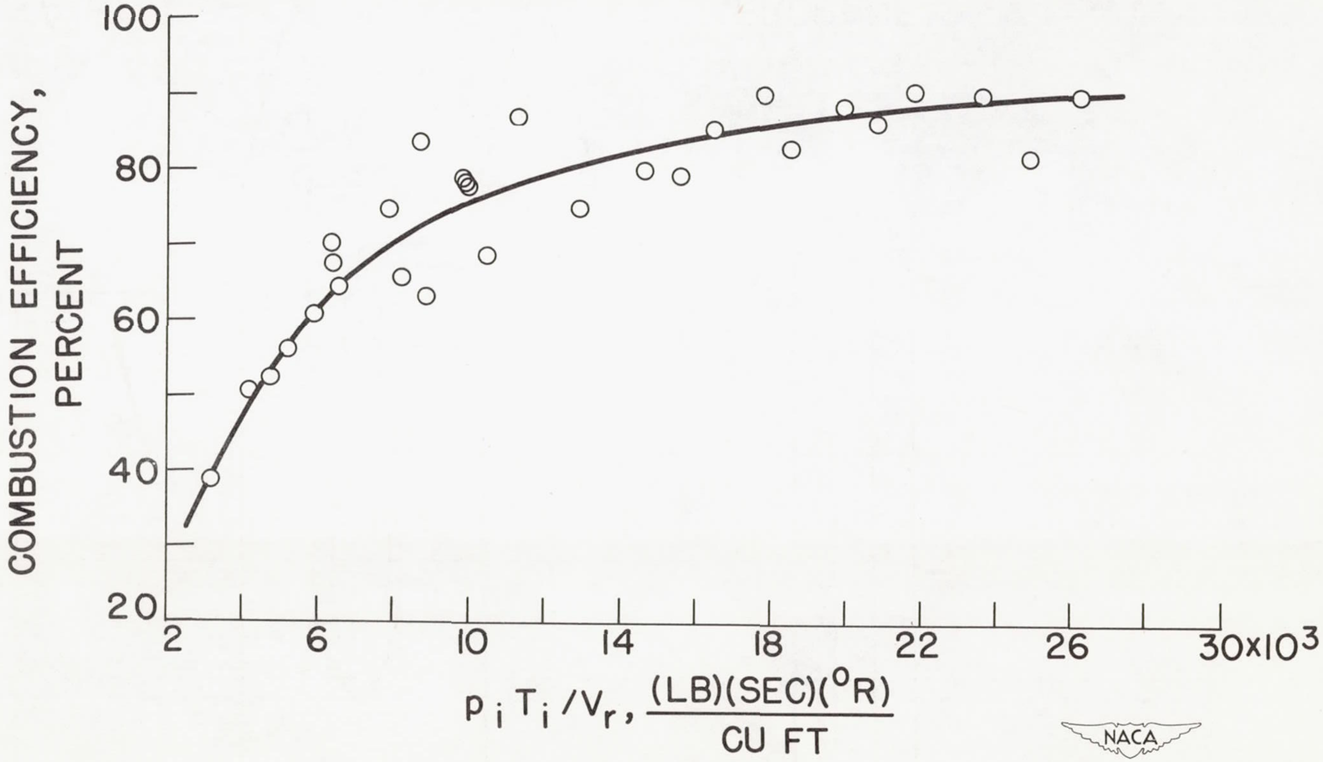

(b) Combustor I.

Figure 11. - Concluded. Correlation of combustion efficiencies at different operating conditions.

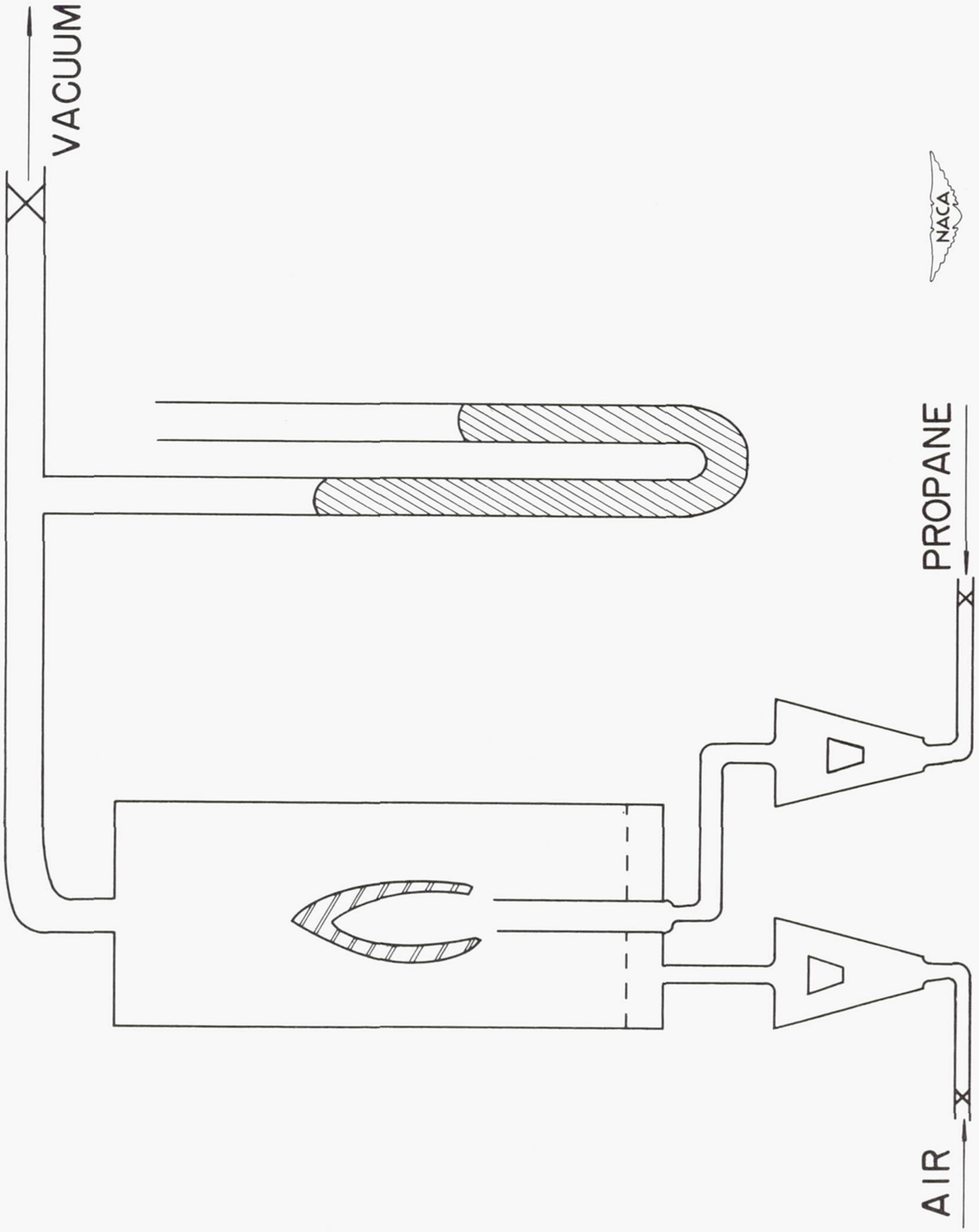

Figure 12. - Diffusion flame apparatus.

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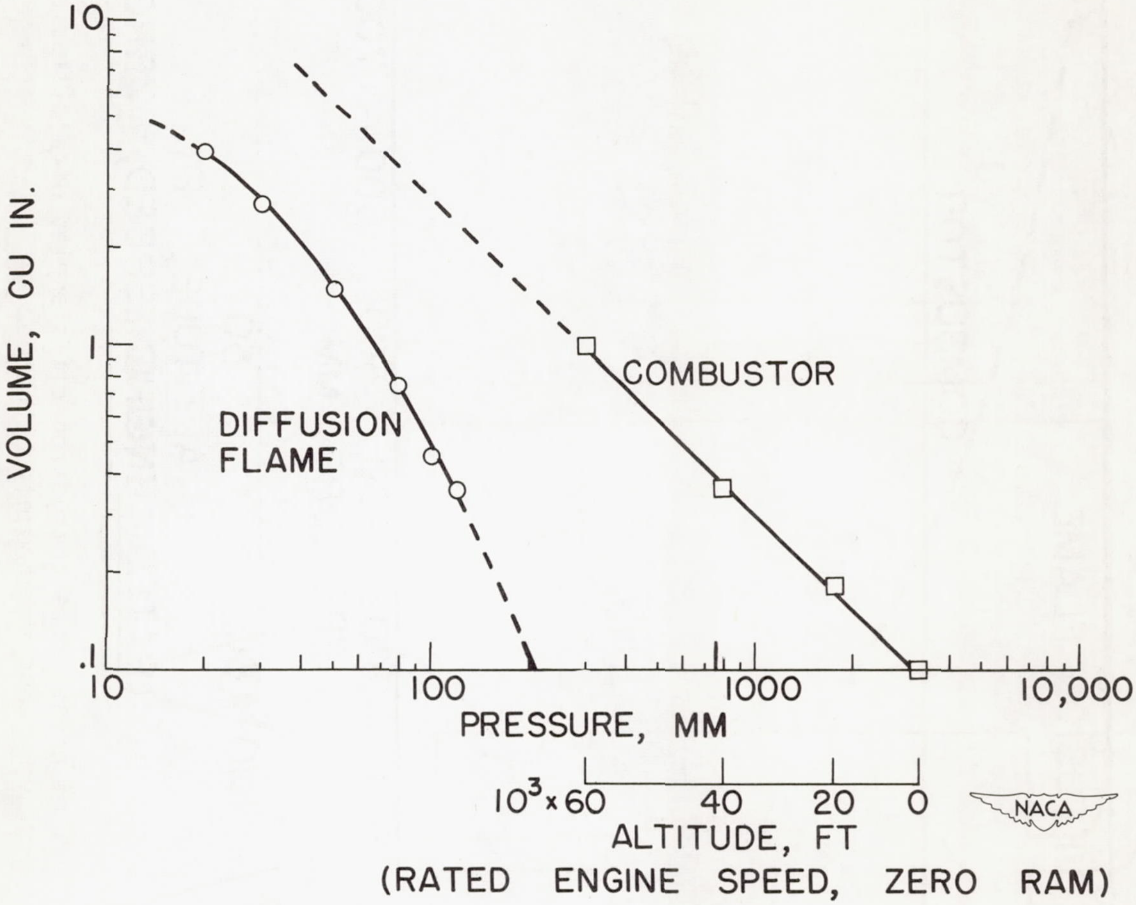

Figure 13. - Effect of pressure on volume required by diffusion flame to release 1000 Btu per hour and corresponding volume available in a turbojet combustor at design fuel flow rates.

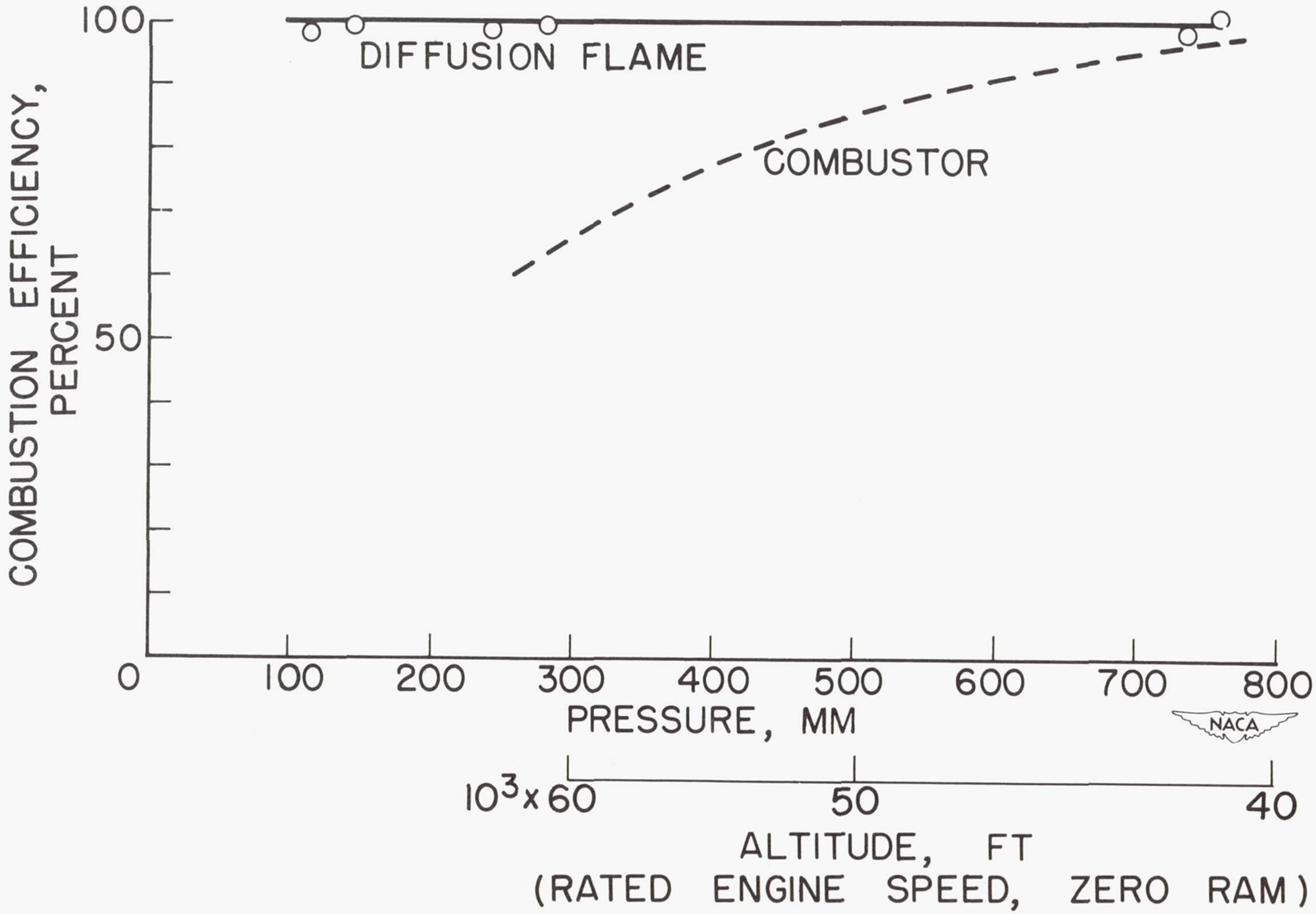

Figure 14. - Effect of pressure on combustion efficiencies of a diffusion flame and a turbojet combustor.

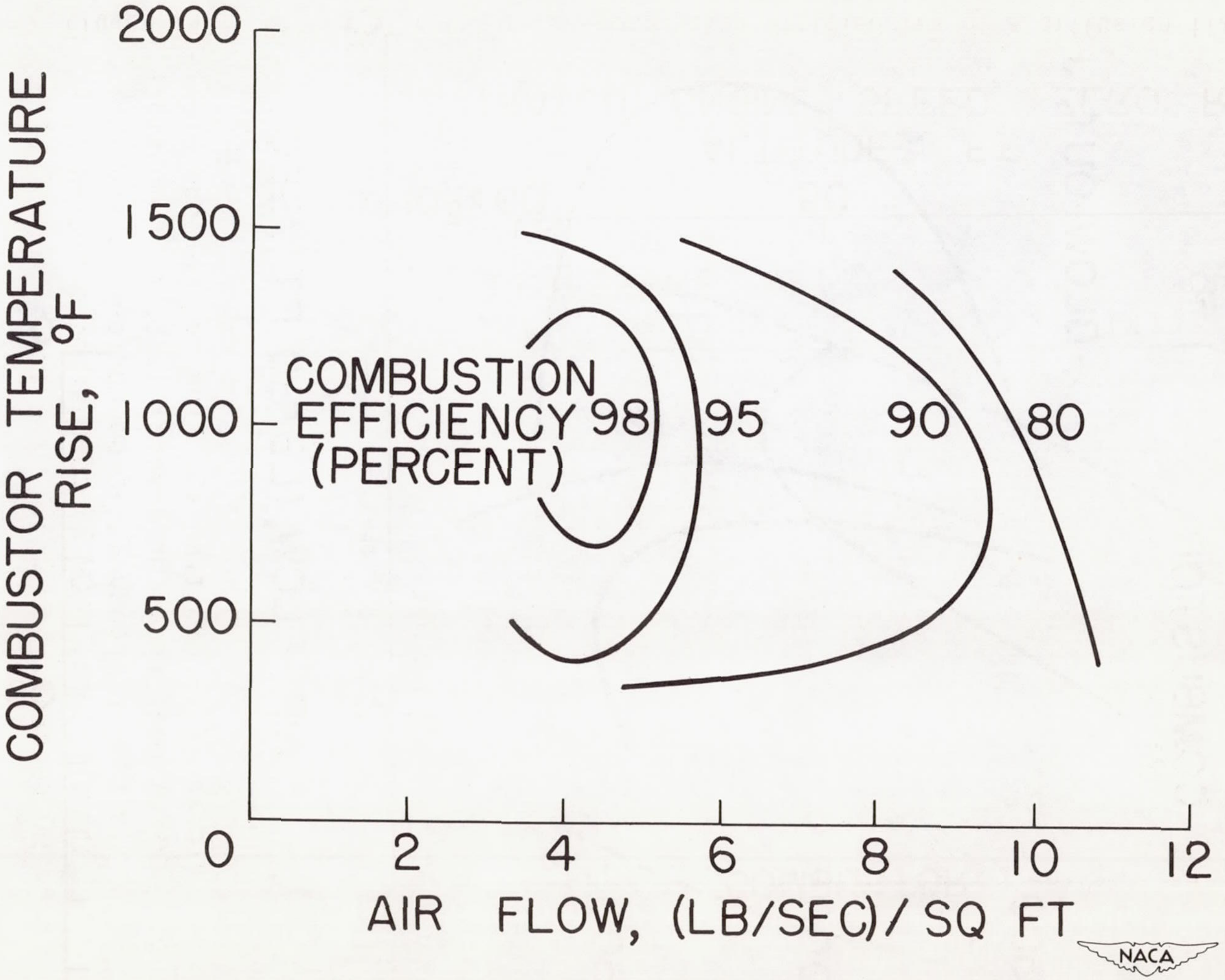

Figure 15. - Effect of air flow per maximum cross-sectional area on combustion efficiency of a turbojet combustor. Inlet-air pressure, 15 pounds per square inch; temperature, 620° R.

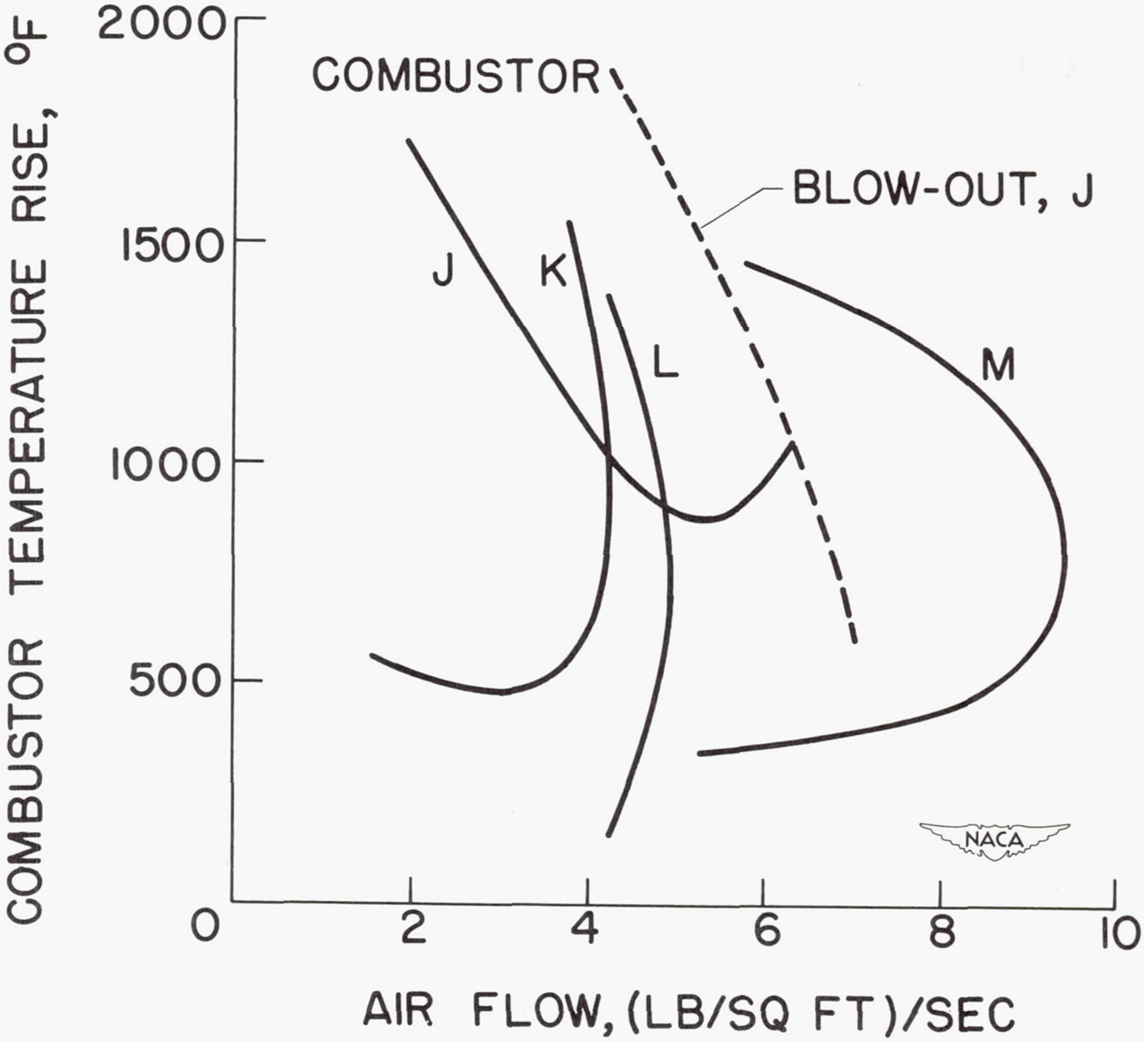

Figure 16. - Limiting air flow per maximum cross-sectional area for several turbojet combustors. Inlet-air pressure, 15 pounds per square inch; temperature, 620° R; combustion efficiency, 90 percent.

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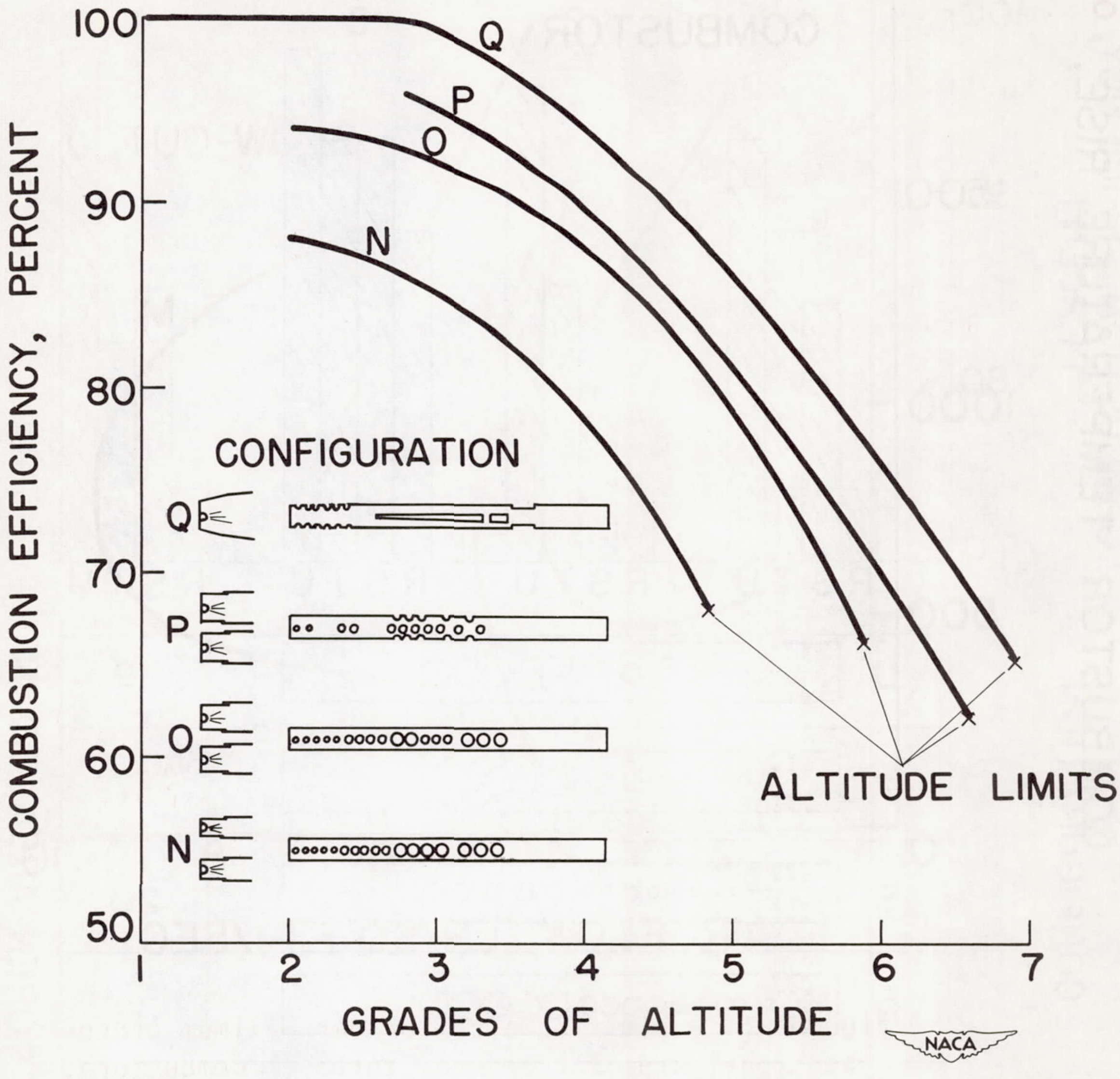

Figure 17. - Effect of design of primary zone on combustion efficiency of a turbojet combustor at full engine speed.

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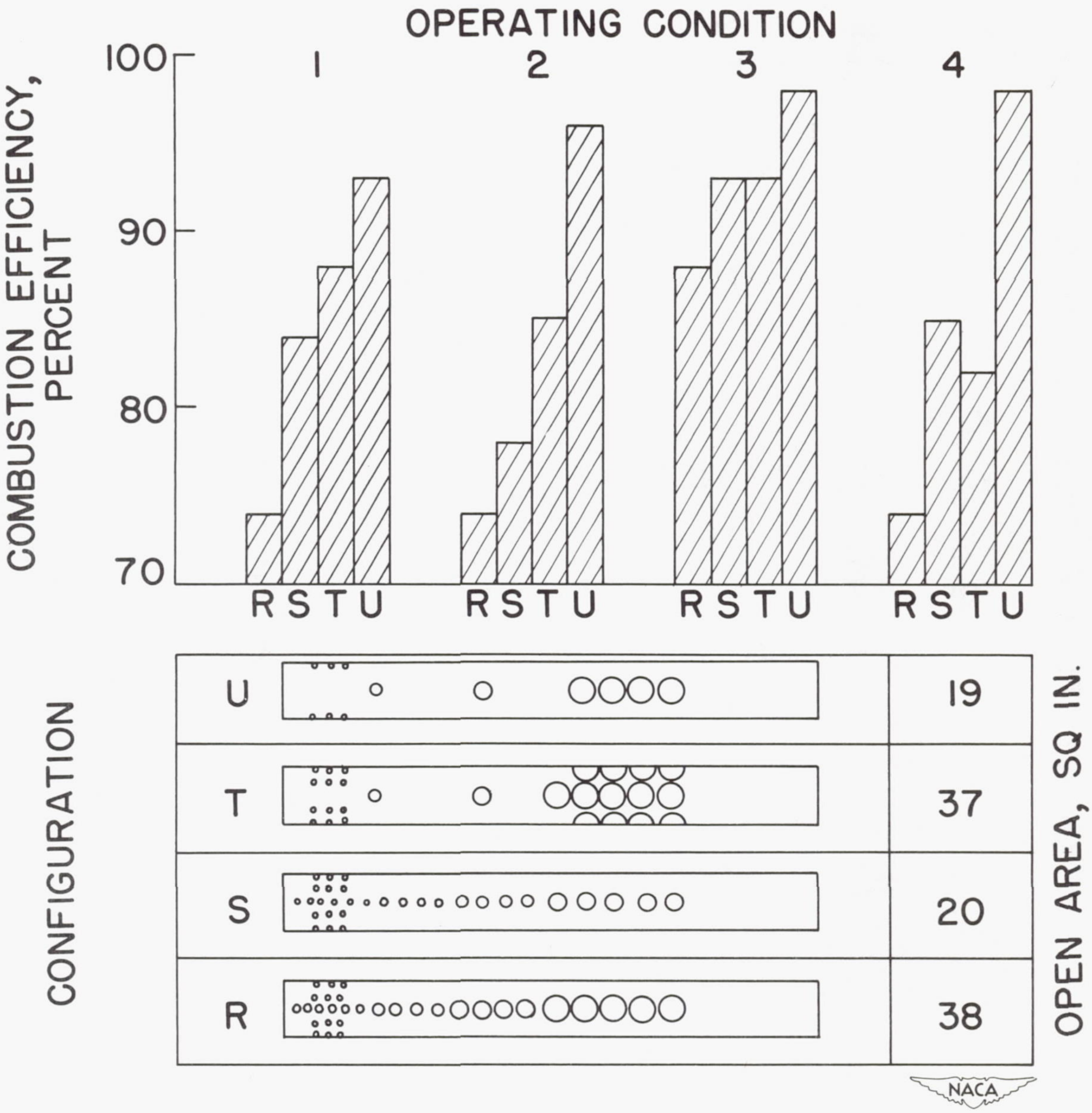


Figure 18. - Effect of total open area and distribution of liner perforations on combustion efficiency of a turbojet combustor at four combustor operating conditions.

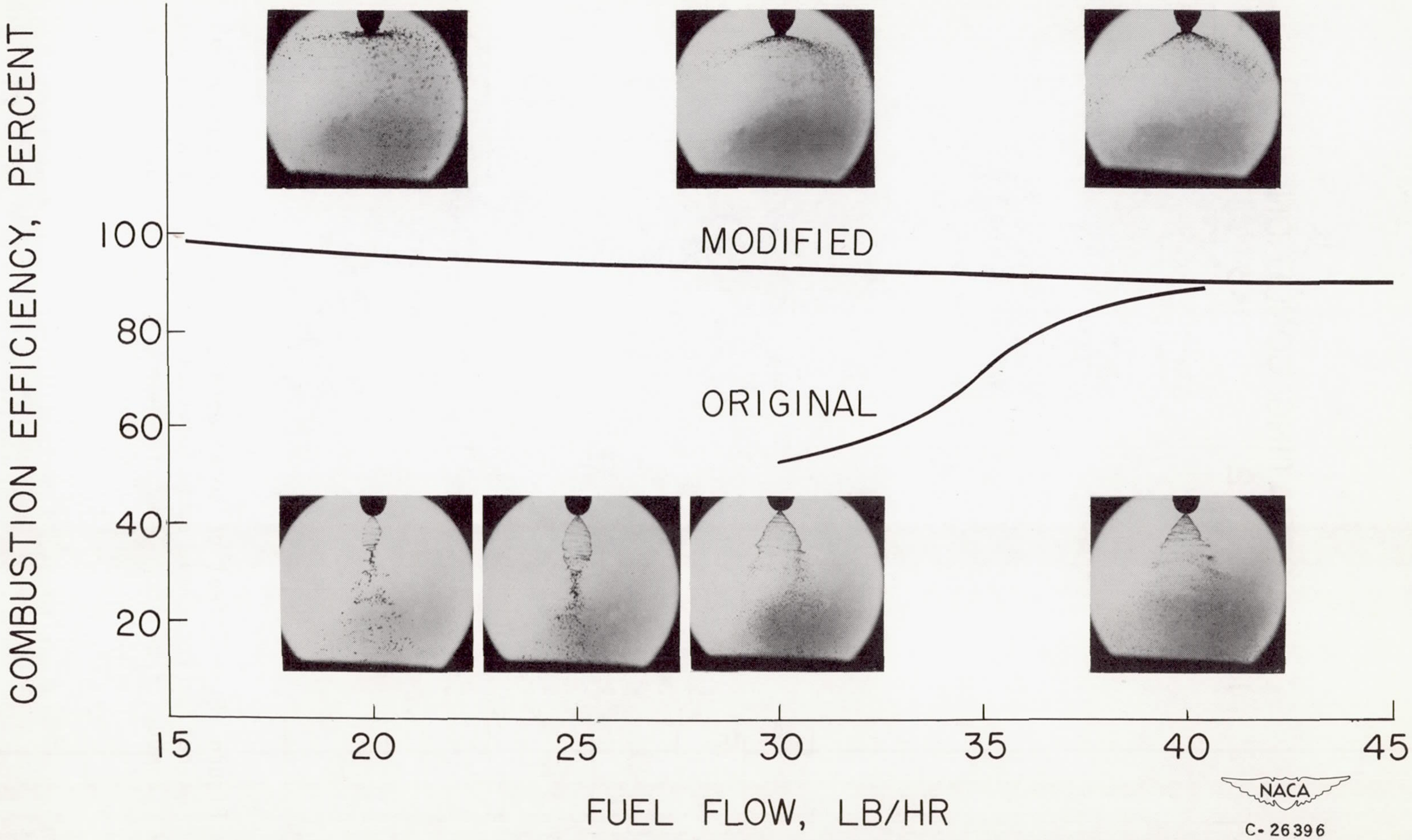


Figure 19. - Effect of fuel-spray configuration on combustion efficiency of turbojet combustor. Inlet-air pressure, 6.1 pounds per square inch; temperature, 90° F; air weight flow, 0.457 pound per second.

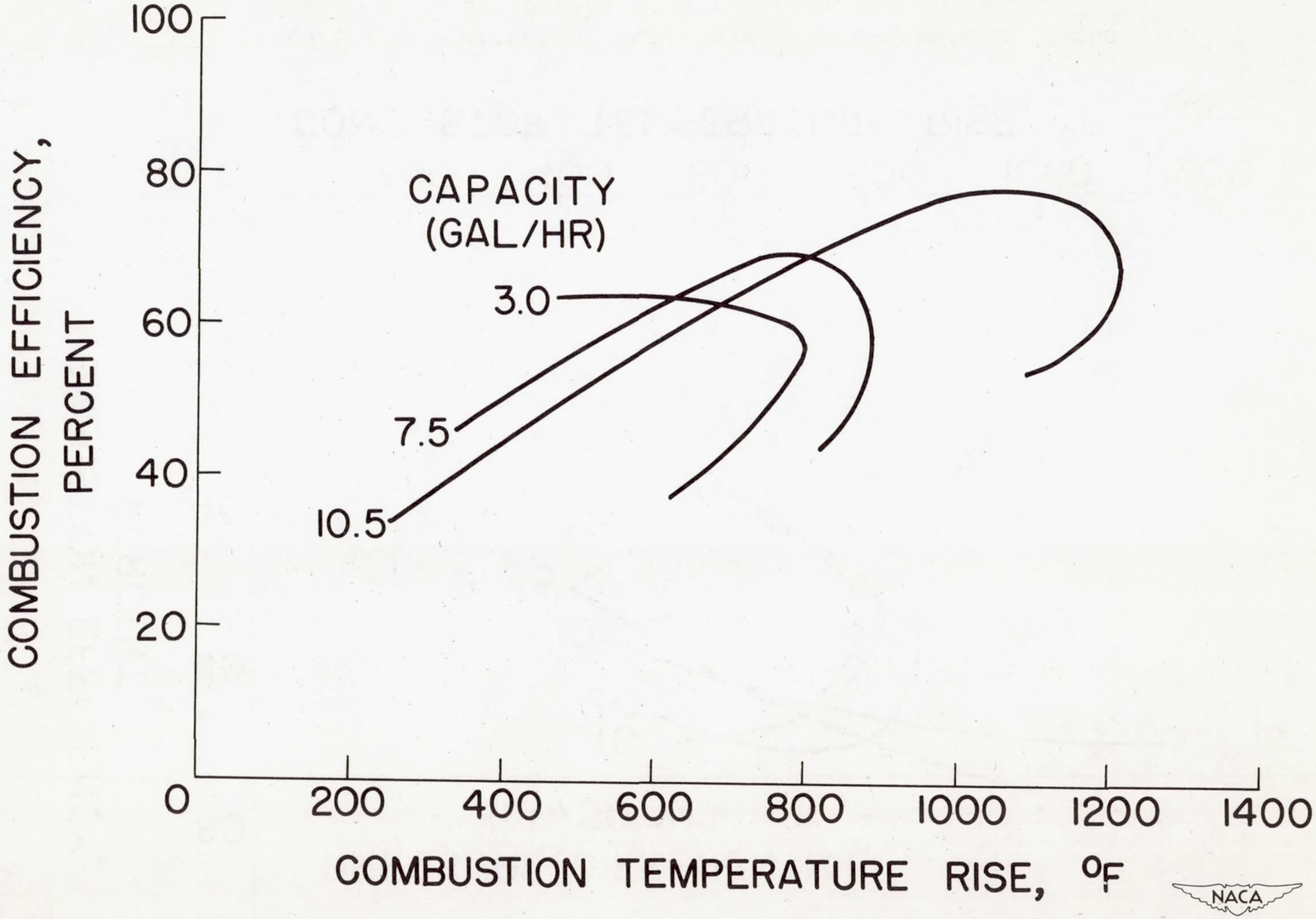


Figure 20. - Effect of capacity of fuel-injection nozzles on combustion efficiency of a turbojet combustor.

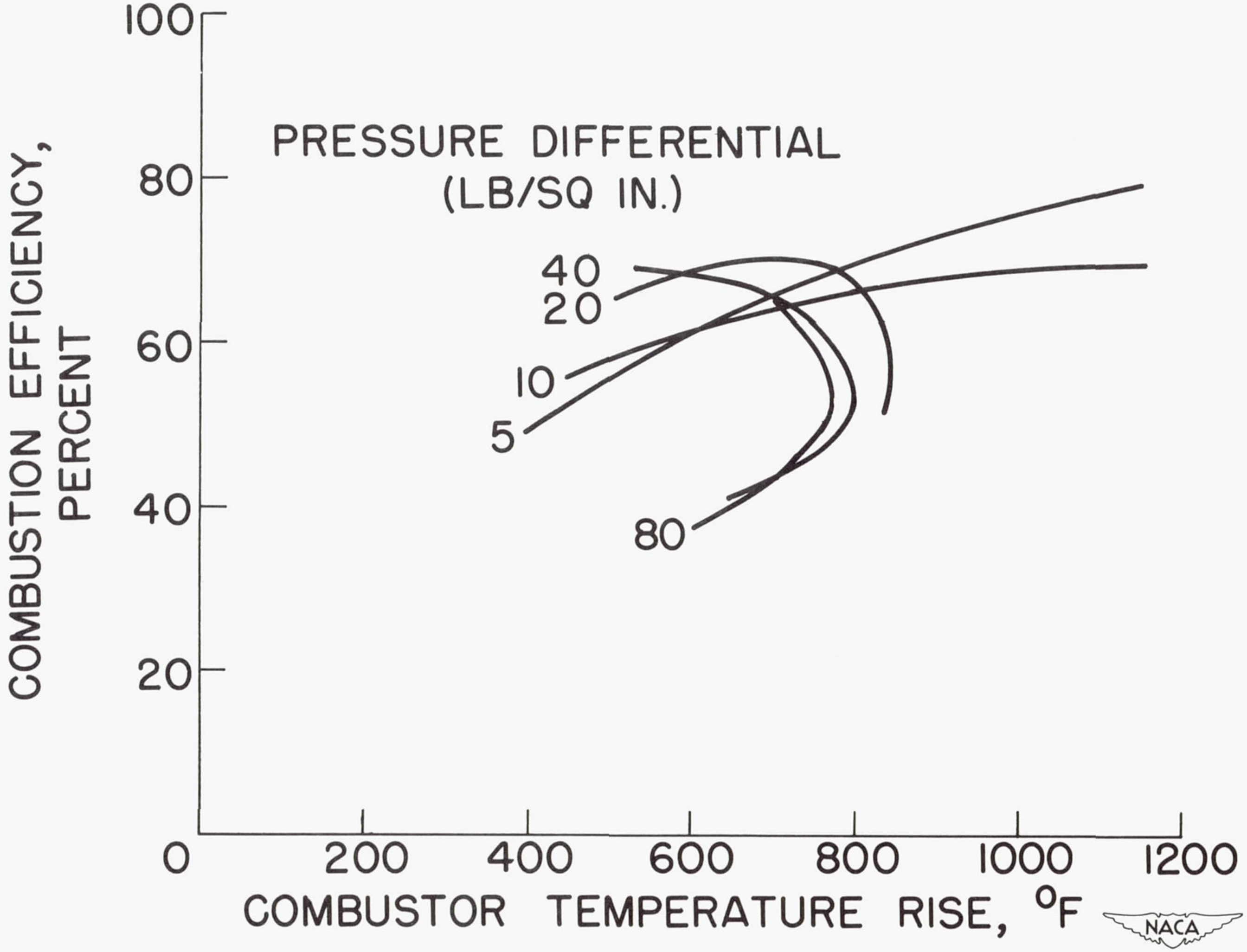


Figure 21. - Effect of fuel-injection pressure on combustion efficiency of a turbojet combustor.

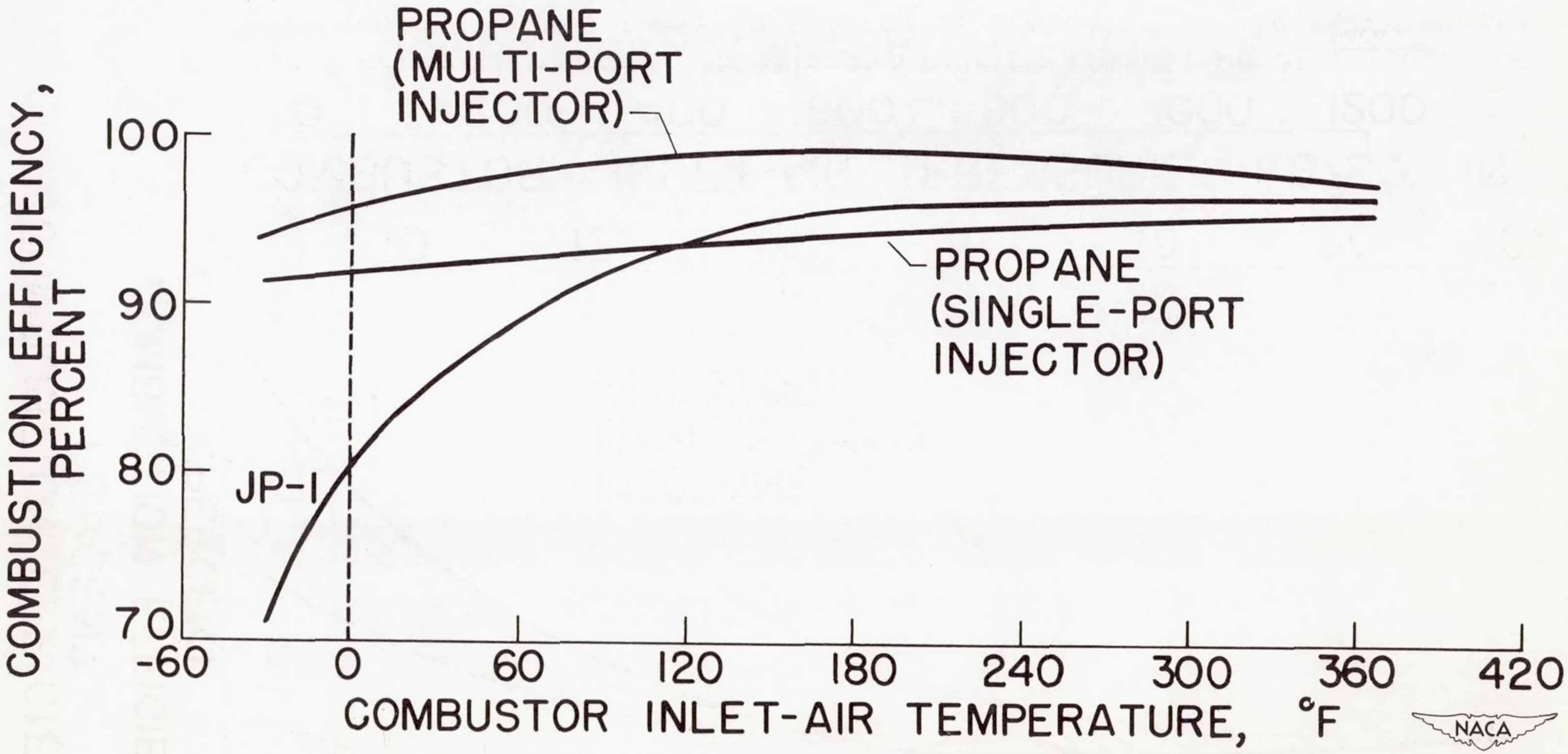


Figure 22. - Effect of inlet-air temperature on combustion efficiency for gaseous and liquid fuels in a turbojet combustor. Inlet-air pressure, 15 pounds per square inch; temperature rise; 1200° F; reference velocity, 80 feet per second.

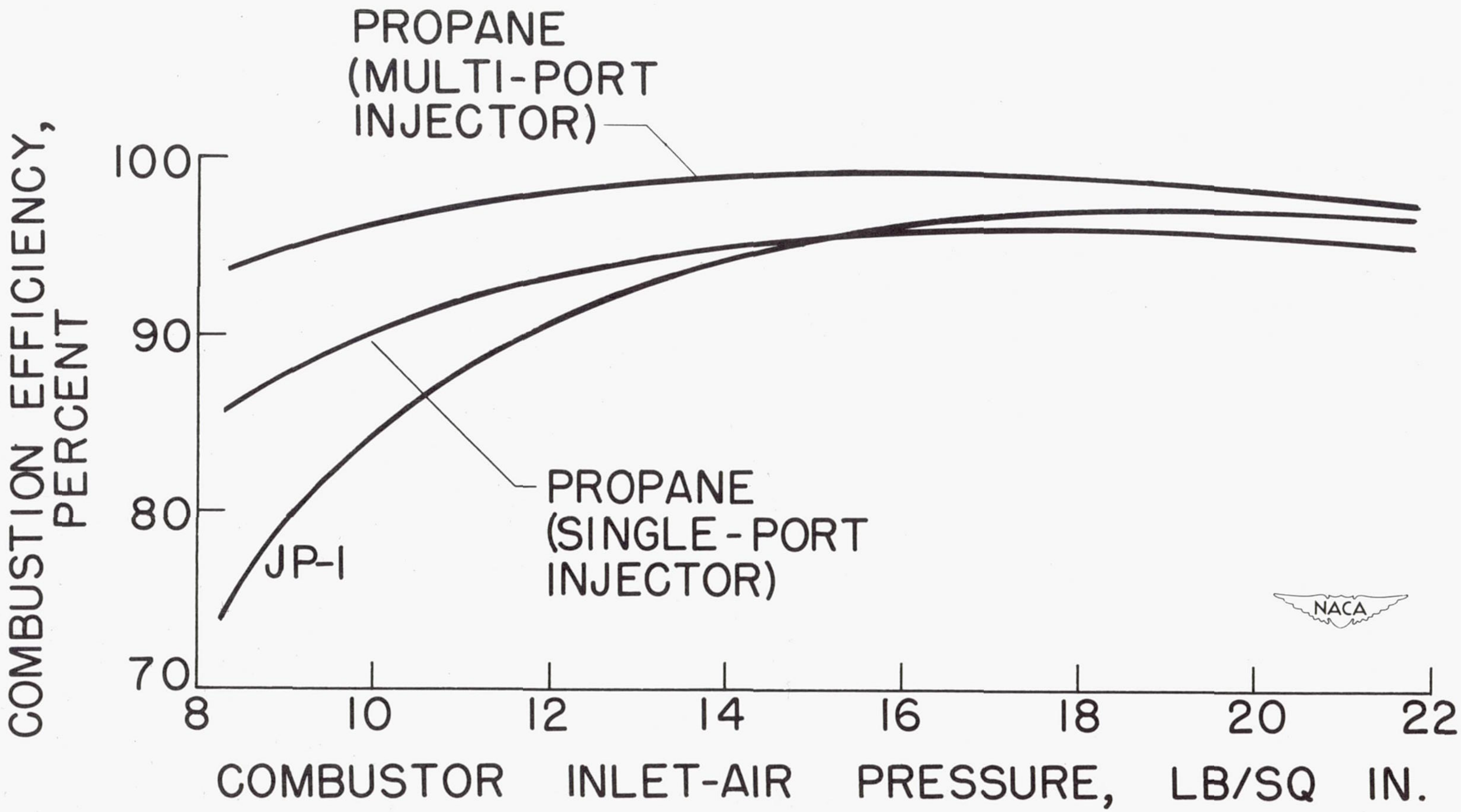


Figure 23. - Effect of inlet-air pressure on combustion efficiency for gaseous and liquid fuels in a turbojet combustor. Inlet-air temperature, 160° F; reference velocity, 80 feet per second; temperature rise, 1200° F.

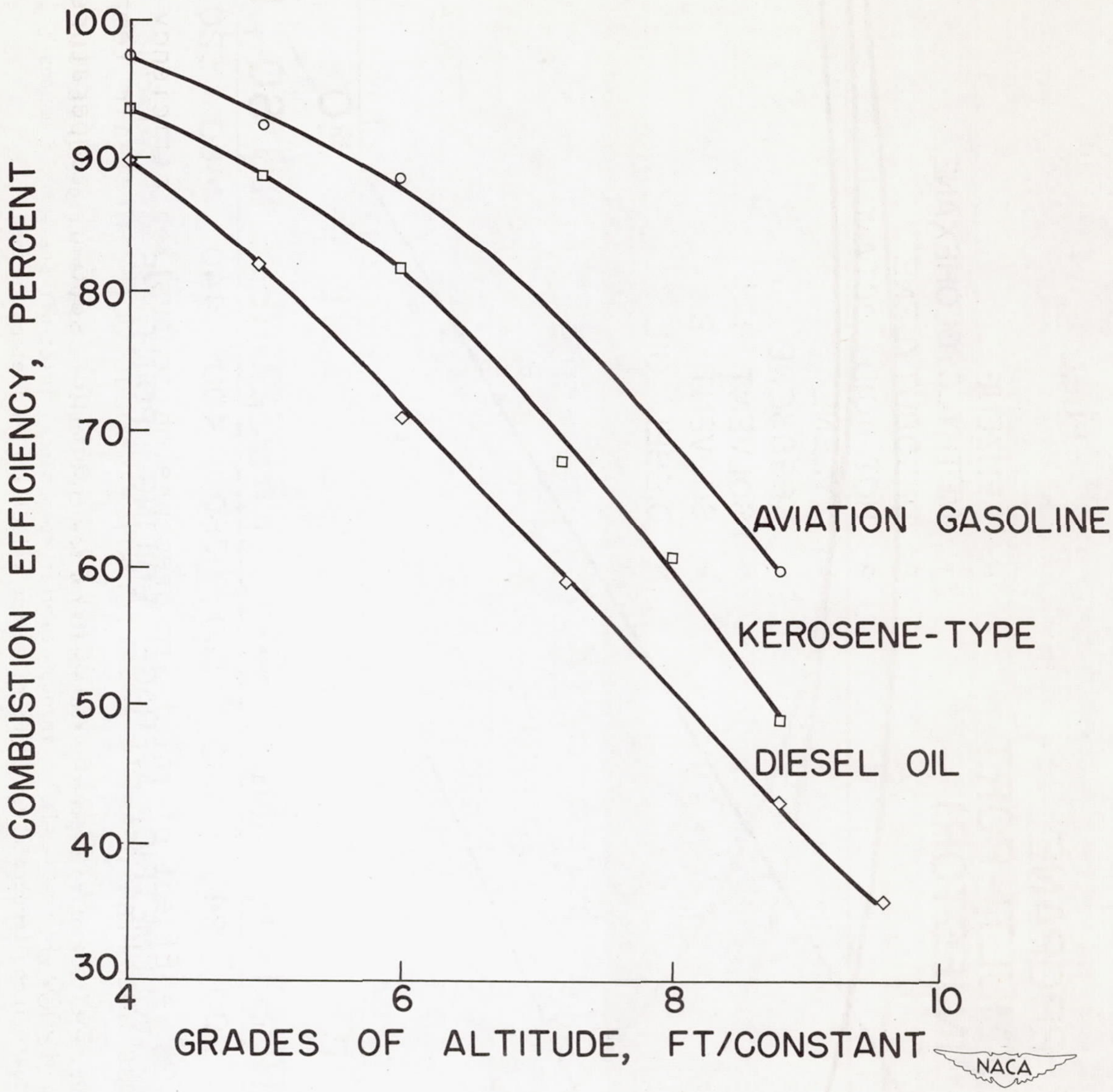


Figure 24. - Variation of combustion efficiency with altitude for three fuels in an annular combustor at 88-percent rated engine speed.

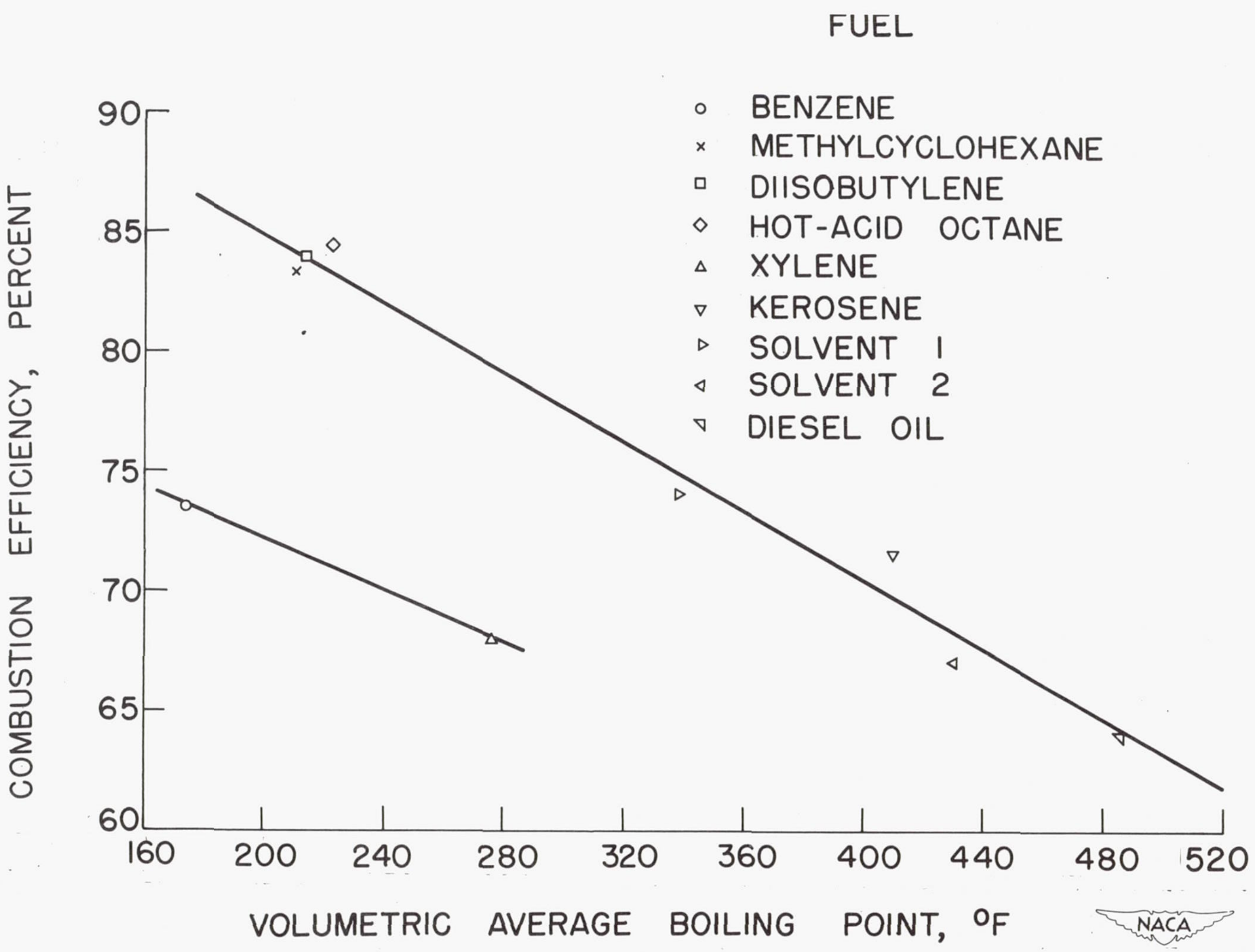


Figure 25. - Effect of volumetric average boiling point of fuels on combustion efficiency at mean temperature rise of 1050° F through tubular combustor. Inlet-air pressure, 6 pounds per square inch; temperature, 75° F; reference velocity, 111 feet per second.

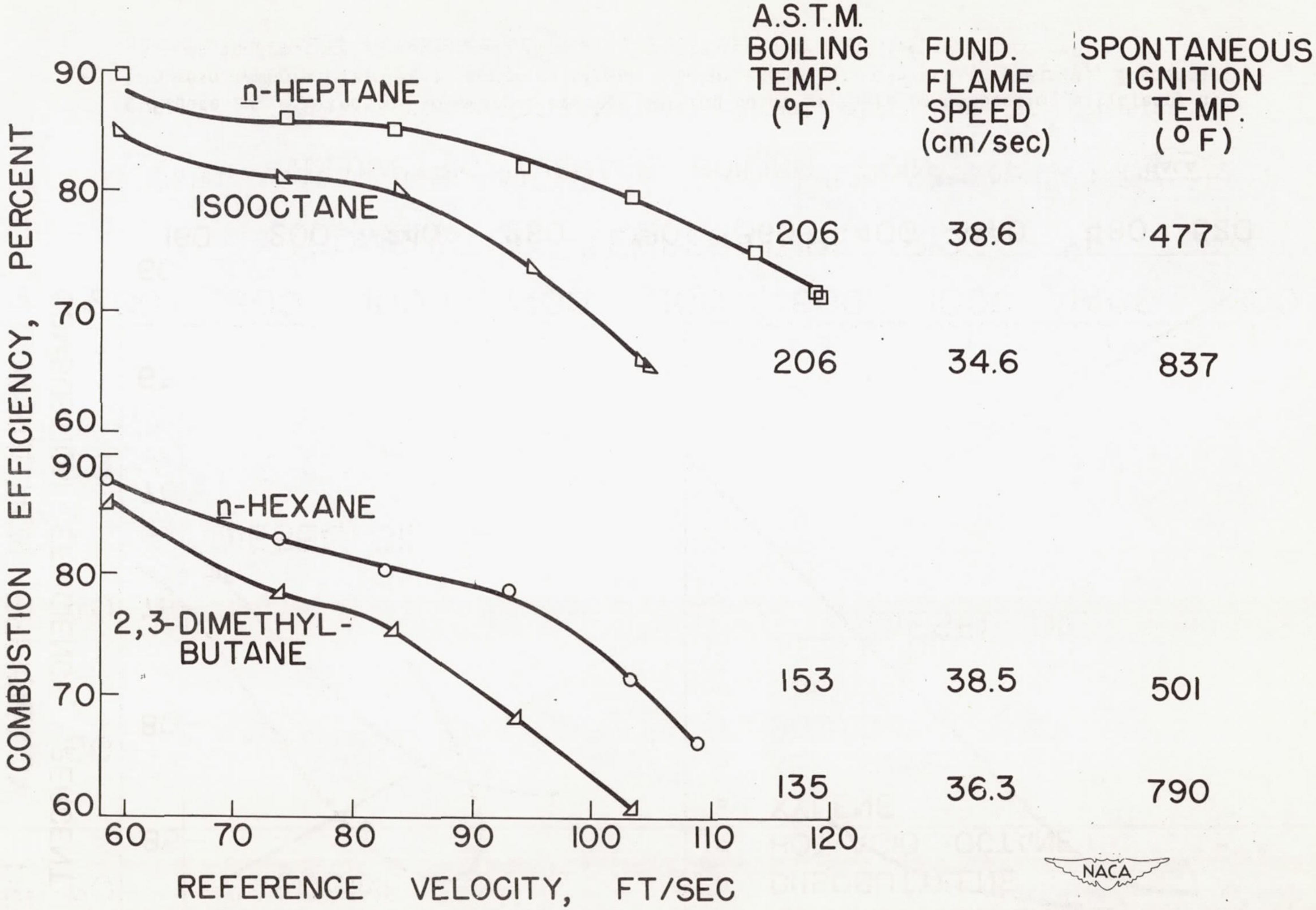
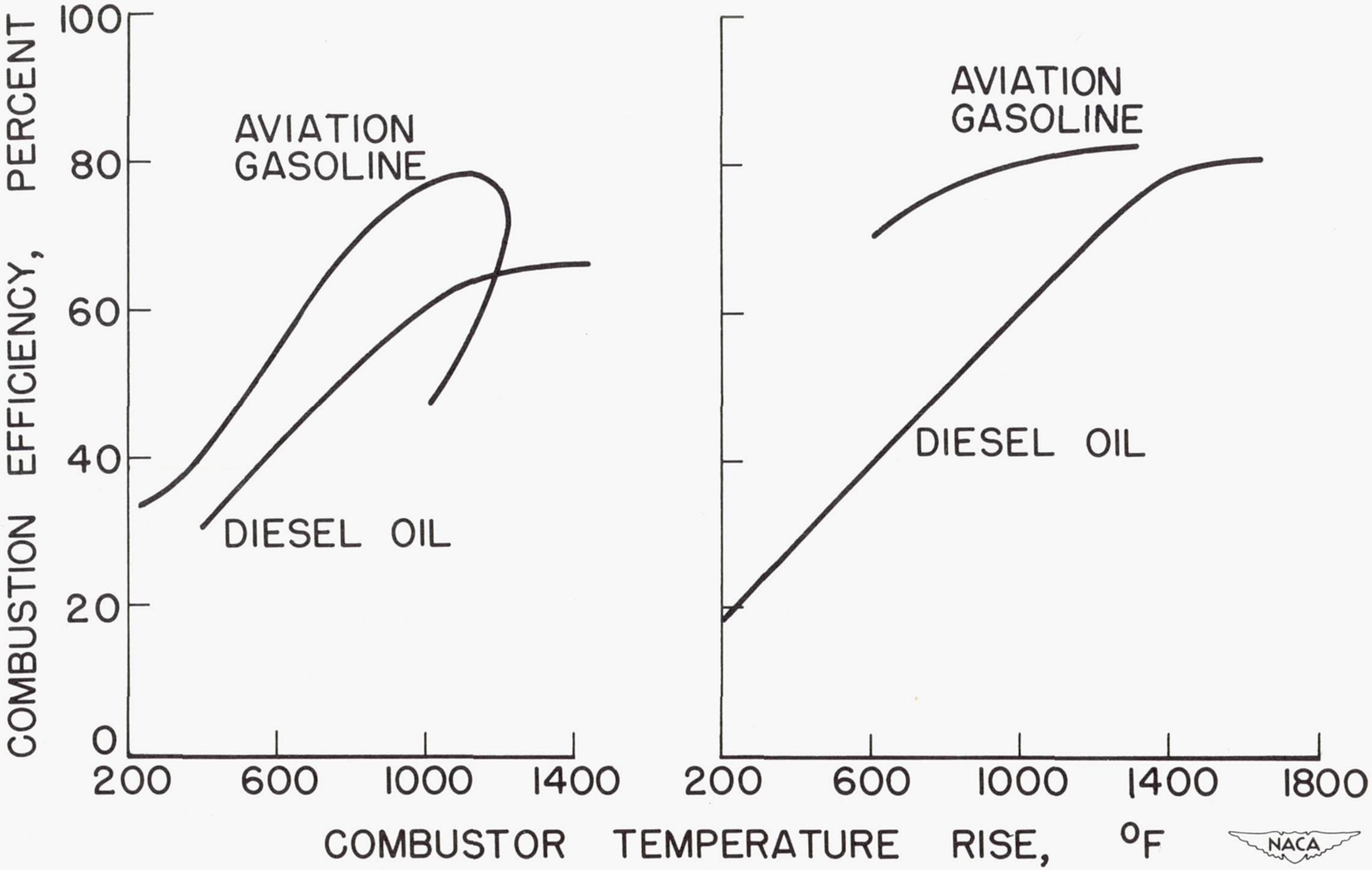
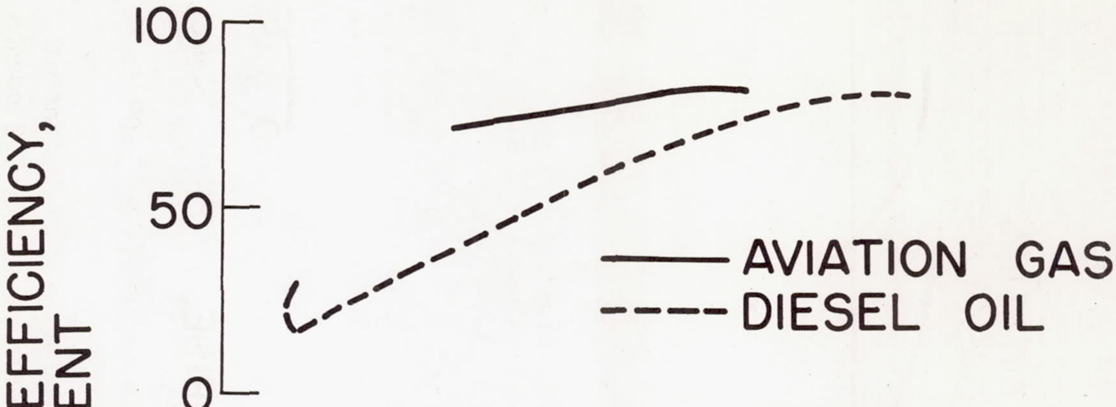


Figure 26. - Variation of combustion efficiency of four pure hydrocarbon fuels with reference velocity in a tubular combustor. Combustor inlet-air pressure, 7 pounds per square inch; temperature, 40° F.

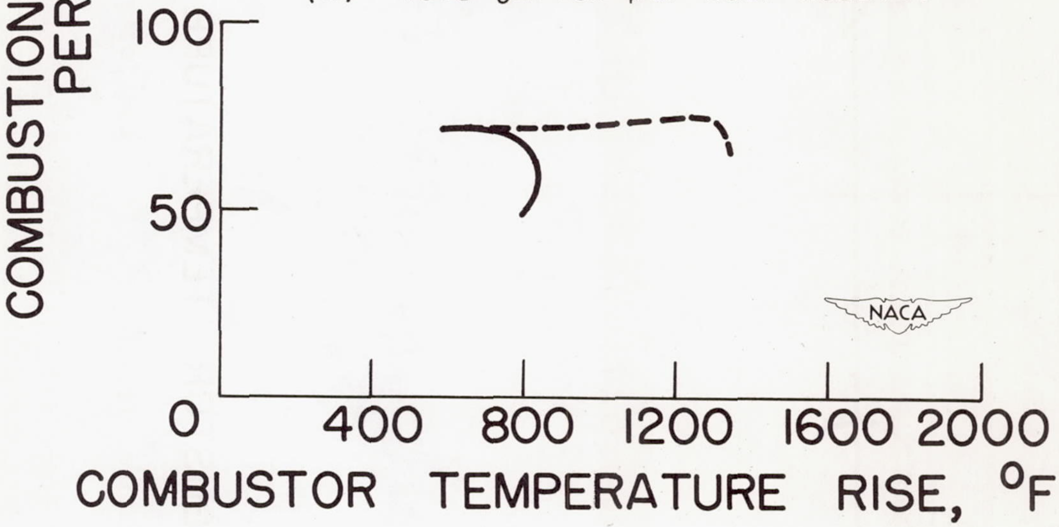


(a) Inlet-air temperature, 150° F.　　(b) Inlet-air temperature, 240° F.

Figure 27. - Relative combustion efficiency of two fuels in annular combustor at two combustor inlet-air temperatures. Combustion inlet-air pressure, 9.2 pounds per square inch; reference velocity, 200 feet per second.



(a) 10.5-gallon-per-hour nozzle.



(b) 3.0-gallon-per-hour nozzle.

Figure 28. - Relative combustion efficiency of two fuels and two fuel-injection nozzles in annular combustor. Combustor inlet-air pressure, 9.2 pounds per square inch; temperature, 240° F; reference velocity, 200 feet per second.